Technical Summary Report 2 *Covering the Period 1 December 1963 to 1 June 1964*

AN INVESTIGATION OF THE APPLICATION OF MODERN SPARK GAP TECHNIQUES TO HIGH-POWER TRANSMITTER DESIGN

By: LAMBERT T. DOLPHIN, JR. ARTHUR F. WICKERSHAM, JR.

Prepared for:

OFFICE OF NAVAL RESEARCH
WASHINGTON, D. C.
AND
ADVANCED RESEARCH PROJECTS AGENCY
WASHINGTON, D. C.

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By: LAMBERT T. DOLPHIN, JR. ARTHUR F. WICKERSHAM, JR.

SRI Project 4548

Approved: R. L. LEADABRAND, MANAGER
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ABSTRACT

Novel methods for generating high pulse and CW powers at HF and VHF were suggested several years ago by scientists at the University of New England, New South Wales, Australia. Calculations indicate that peak powers of at least tens or hundreds of megawatts could be expected.

The practical and engineering problems of realizing working transmitters have prompted the research described in this report. Although the ideas are novel and challenging, many practical problems and obstacles to success have been encountered. This report discusses the transmitting devices proposed by the Australian workers and research that has been done towards development of practical working models. We conclude that the techniques remain promising but that careful consideration of engineering problems is essential to success and future application of these devices.

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I INTRODUCTION

In recent years scientists working under the leadership of Dr. Kurt Landecker at the University of New England in Australia, have proposed several schemes for the generation of very-high-frequency radio signals by the use of capacitor storage and impulsive discharge techniques. The interesting possibilities of these methods, the soundness of the theoretical arguments, and the necessity of investigating the engineering problems have led to the research project described in this report. This project is sponsored by the Advanced Research Projects Agency under ARPA Order 463, and the Office of Naval Research, Contract Nonr-4178(00).

The original Australian work is described in Australian Patent No. 233,302 and is summarized in an article in the Australian Journal of Physics.[1*] The current program at Stanford Research Institute (SRI) has entailed a thorough investigation of the Australian ideas and an exploration of the engineering features that limit or restrict these novel transmitter devices. Technical Summary Report 1 on this contract, January 1964, describes our earlier work. While the original transmitter proposed by Landecker involved only a circular array of capacitors, charged parallel and discharged in series by means of spark gaps, the basic ideas have grown to include a wide variety of related power-generating schemes that also are under investigation.

This report is an extension of the previous Technical Summary Report, and background material concerning the Australian work and earlier SRI research is not repeated here.

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* References are listed at the end of this report.

II HIGH-POWER HF RING TRANSMITTER

A. Construction Details

As a result of earlier experiments with the basic ring transmitter configuration it was decided to build a high-power ring transmitter for operation at a nominal frequency of 20 Mc. The design characteristics of this transmitter are listed in Table I. This transmitter was first tested in a simple configuration and then modified extensively to test other ideas.

Table I

DESIGN CHARACTERISTICS OF 20-Mc RING-SPARK TRANSMITTER

PARAMETER	PRIMARY RING	SECONDARY RING
Number of Capacitors, N	67	40
Capacitance per unit, C_i	356 ± 1 pf	356 ± 1 pf
Inductance of total ring, L	11 μh	7.1 μh
Capacitance of all units in series, C	5.3 pf	8.9 pf
Charging voltage	20-120 kv	0
Energy storage at 50 kv	30 joules	0
Peak power averaged over transmitted pulse at 50 kv	17 Mw	--
Pulse length	1.0 μsec	
Operating quality, Q	65	150
Ring diameter	112 inches	78 inches
Radiation Resistance, R'	23.3 ohms	4.66 ohms

Figure 1 is a photograph showing the construction detail in the ring transmitter. The capacitors were made of copper-clad laminate which is commercially available and has a loss factor less than 0.009, a dielectric constant of 4.8, and a dielectric strength of 65 kv per 1/16 inch. Figure 2 shows the completed ring. The capacitors were charged through resistors made of tygon plastic tubing filled with tap water. Resistances from 1 to 20 megohms were easily obtained by changing the tubing

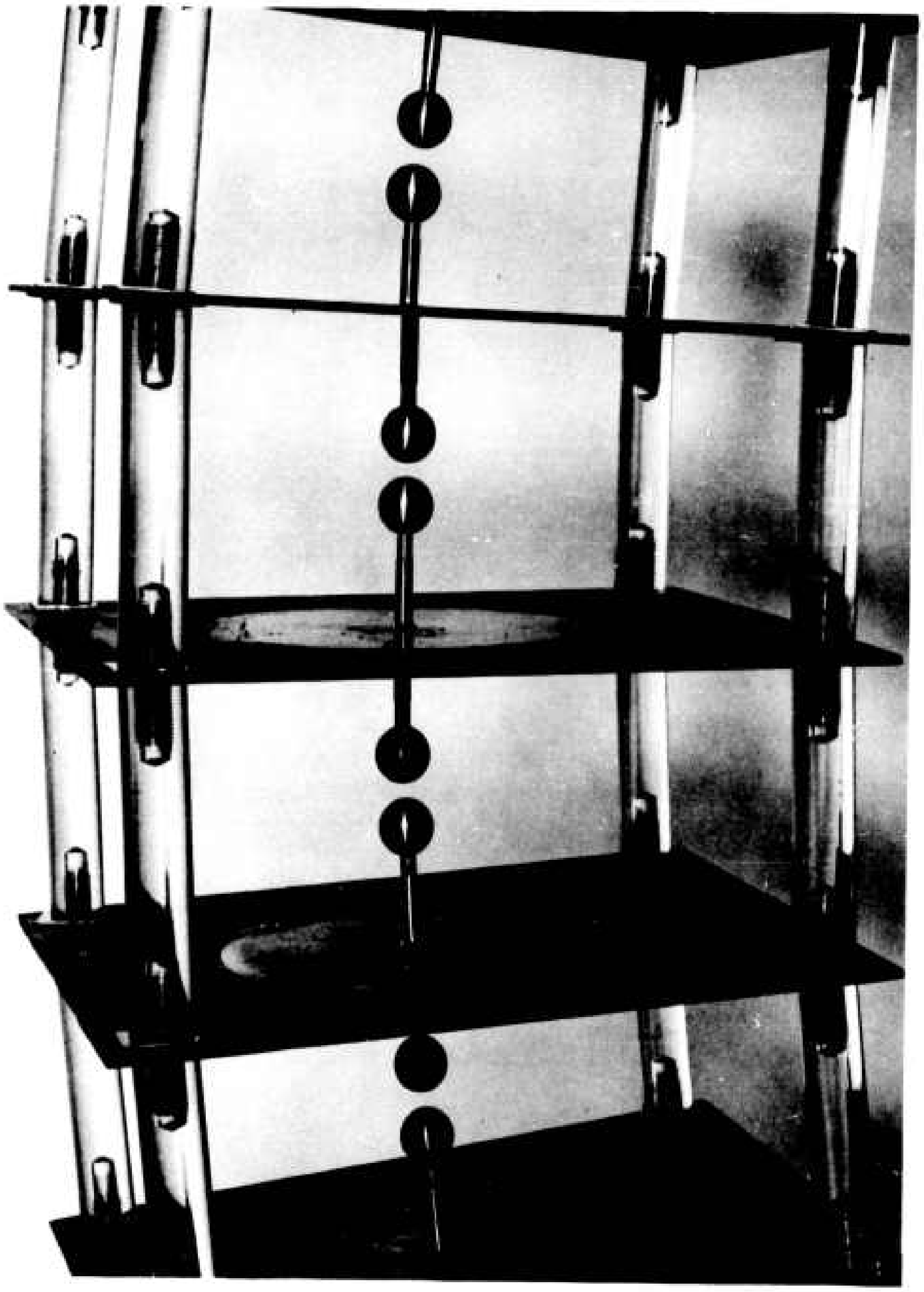


FIG. 1 RING TRANSMITTER SECTION

FIG. 2 20-Mc RING TRANSMITTER

size or adding a little salt to the water. Figure 3 shows the primary and secondary rings spaced at the correct distance for critical coupling. The primary ring was placed on a turntable to permit pattern measurements.

When operation of the ring first was attempted, it was found that large RF voltages were induced in nearby conductors and sparks could be drawn from metallic objects in the laboratory, indicating that high-intensity RF fields were being generated. It was necessary to move to the far field to determine the actual operating frequency and power spectrum of the radiated signal. A receiving station was set up at the Stanford field site, 5.6 km from the transmitter. At this range the operating frequency of 23.5 Mc was measured. Weak echoes from nearby mountains and aircraft were obtained; however, the measured power, as determined from the field strength of the direct signal at the receiver site, indicated a transmitter power of the order of only a few kilowatts, or at most 10 kw. Pulse width was about one microsecond, as expected, and the signal was well defined in frequency. The only unexpected result was the low peak power, about three orders of magnitude too low. By rotating the transmitter ring a 2:1 variation in radiated power was observed, maximum power being observed when the ring was parallel to a line joining transmitter and receiver sites.

In the near field of the antenna spurious frequencies were discovered, and it was evident that some energy was being lost in other modes. The ring probably should be considered a traveling-wave structure. Discontinuities caused by the posts, capacitor plates, and spark gaps might be responsible for the observed, additional modes of oscillation. The spurious frequencies observed in the near field indeed seemed to correspond to dimensions of the posts and spark gaps and it was decided that larger, uniform inductance posts should be installed.

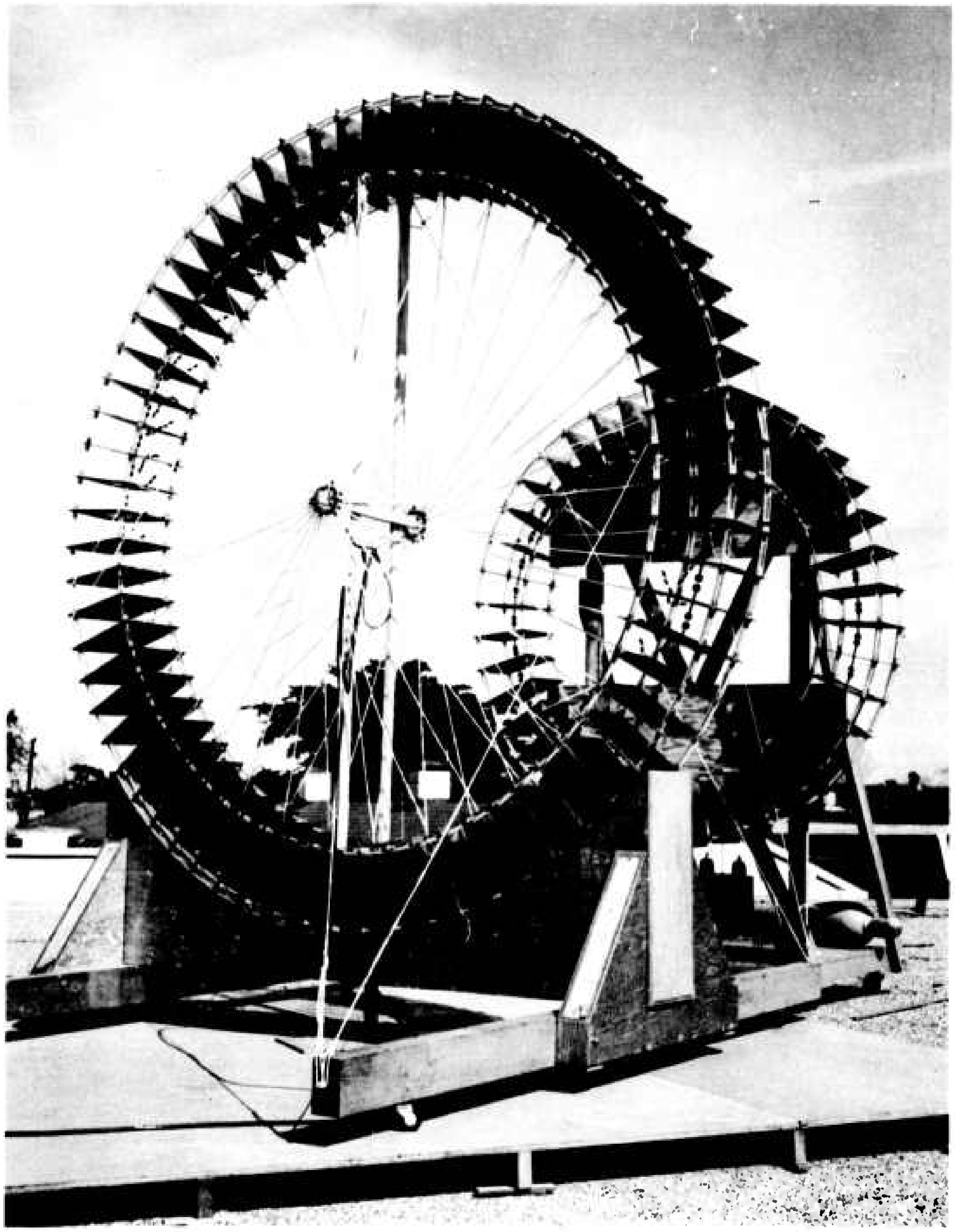


FIG. 3 RING TRANSMITTER WITH SECONDARY

B. Bias Schemes

Suspecting also that high spark losses might be the cause of the low peak power, we next attempted to apply bias current to each spark gap. The original two posts and spark spheres were replaced with a special spark gap which incorporated two additional 500-pf ceramic capacitors. The additional capacitors were connected in parallel with the gap so that they could be discharged through the gap at the same time as the ring capacitors. Figure 4 shows this type of gap with its bias capacitors. The straps that connect the bias capacitors, C_b, to the gap, constitute an inductance L_b; thus, the bias current was actually RF rather than dc. While a hotter spark resulted from this biasing scheme, it was impossible to synchronize the spark gaps. Despite all precautions the gaps could not be made to fire together. Further, the RF pulse from a single gap was found to be a complex mixture of many frequencies. It was found that unless each strap inductance could be carefully adjusted so that the frequency of the bias current coincided

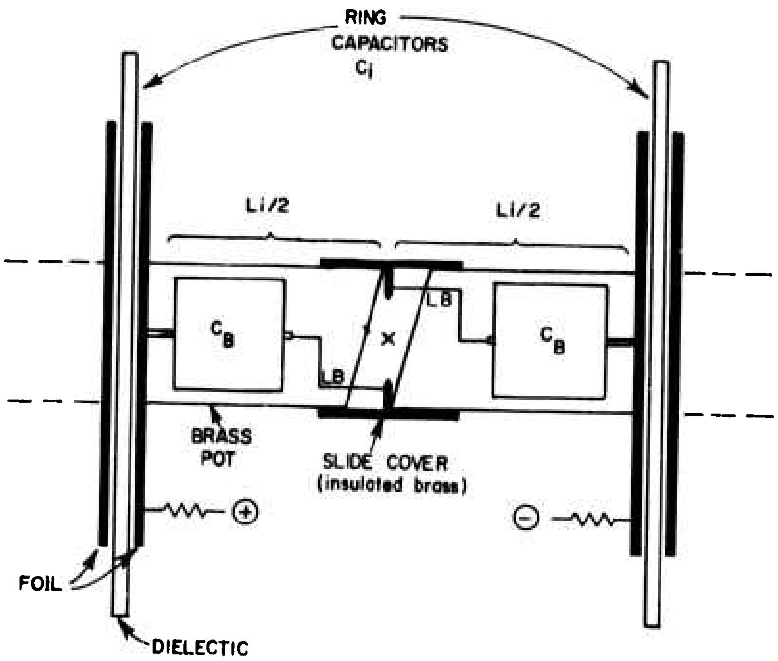


FIG. 4 SPARK GAP WITH INTERNAL BIAS CAPACITORS

with the frequency of the entire ring, the resulting transmitted pulse would not be monochromatic.

Earlier attempts had been made to bias the spark gaps by placing external bias capacitors across the spark gaps, but these attempts resulted in an operation of the ring as two, tightly coupled circuits, and it was impossible to get a reasonably monochromatic pulse. It was expected that enclosing the bias components within the metal shell of the post inductors would eliminate such a problem, but this did not prove to be the case.

W. Millar[2] has experimented with RF and dc biasing of spark discharges. Some of his experiments and work are summarized in Figs. 5 to 8,

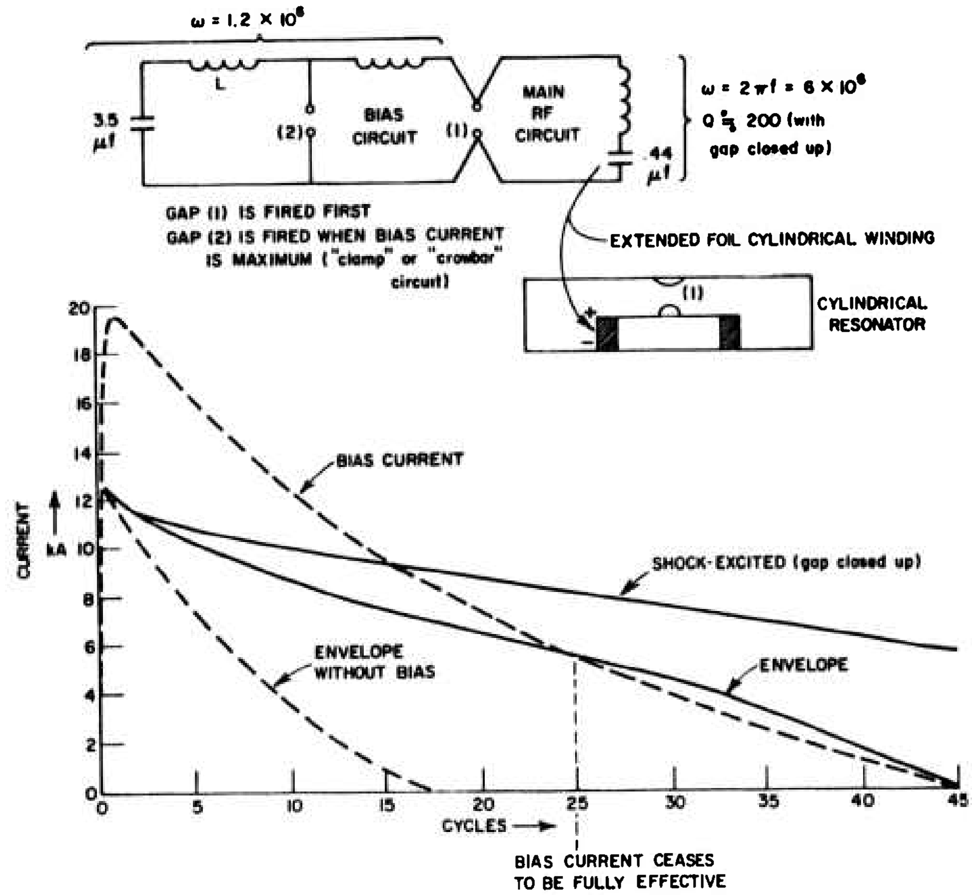


FIG. 5 RF BIAS FOR HIGHER-FREQUENCY OPERATION

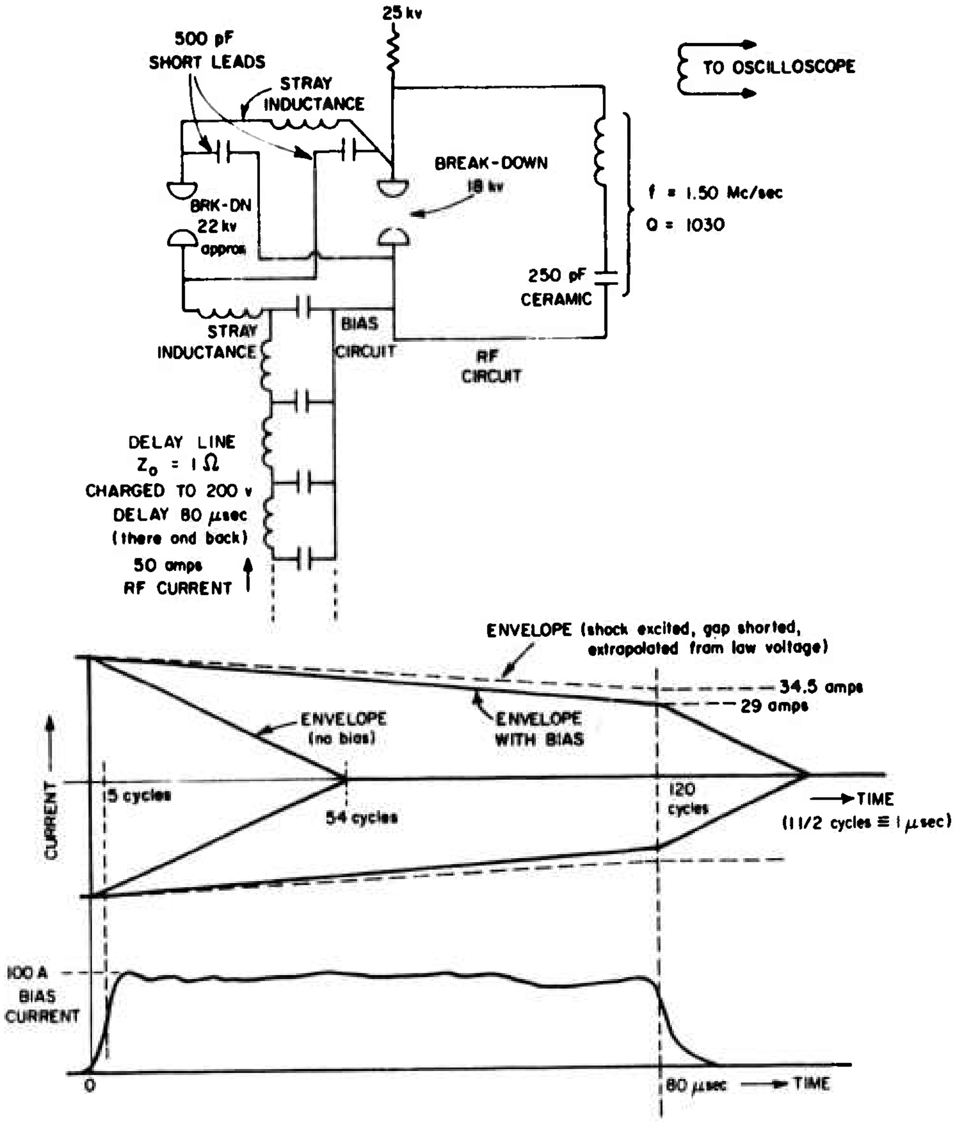


FIG. 6 DC BIAS FOR LOW-FREQUENCY DISCHARGES

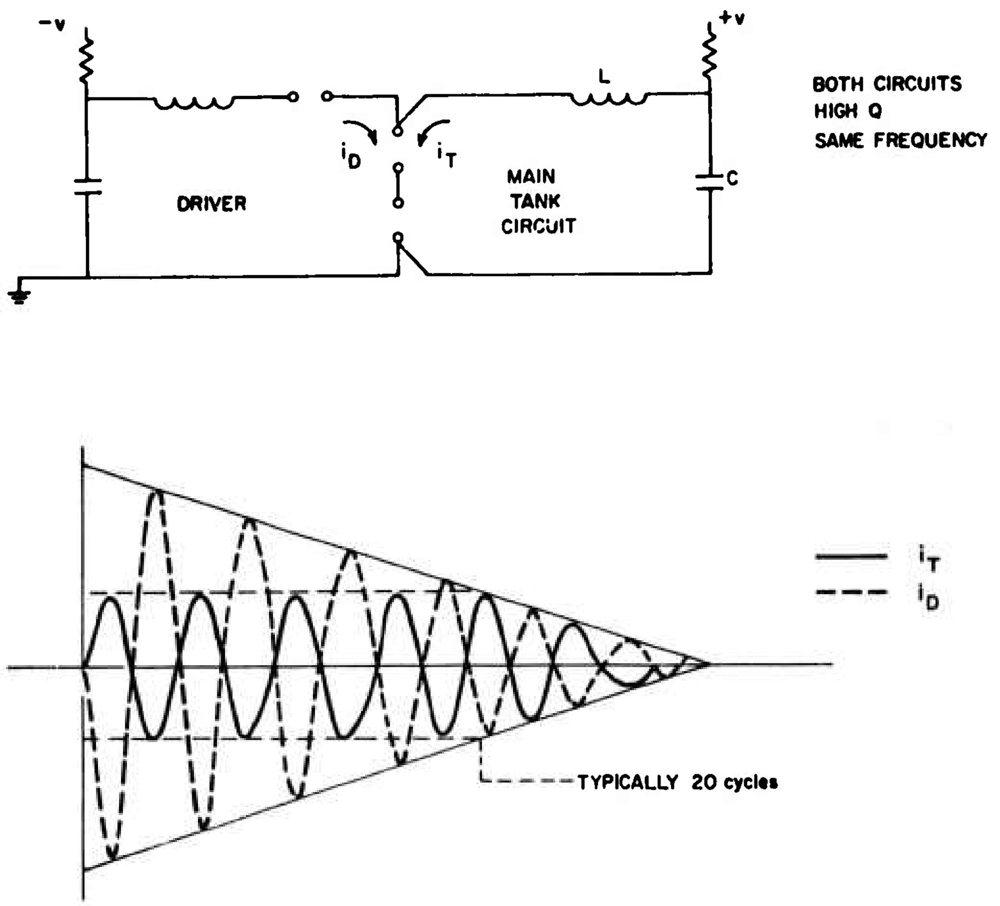


FIG. 7 RF BIAS SCHEME

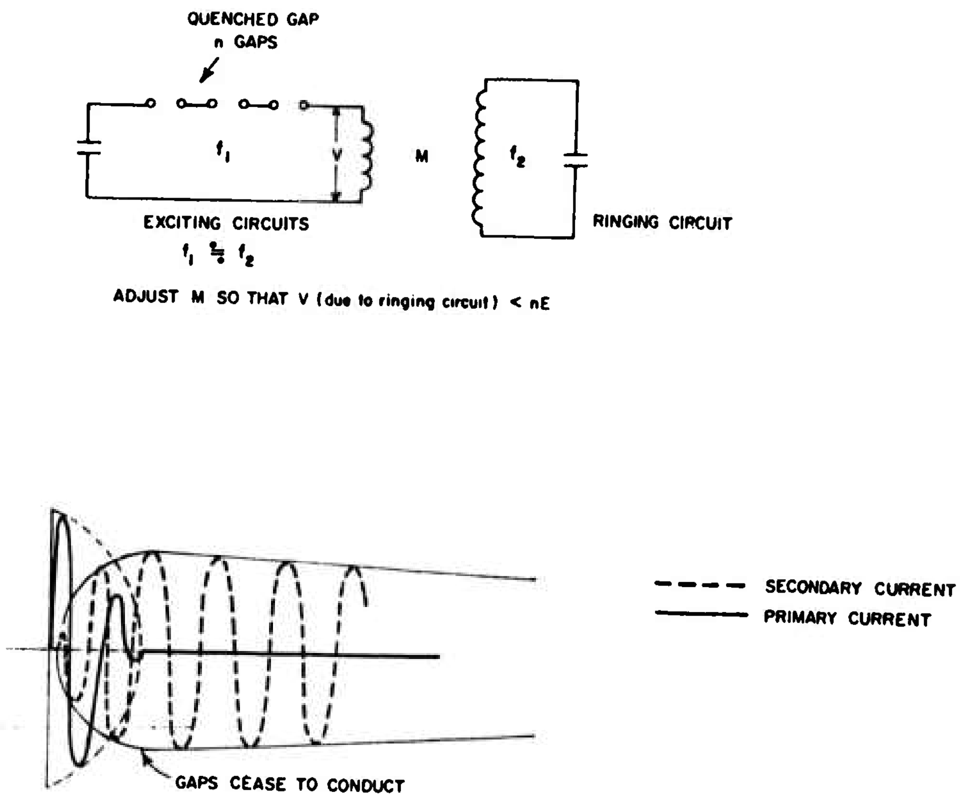


FIG. 8 QUENCHED GAP WITH SECONDARY CIRCUIT

which are self-explanatory. With more than one spark gap, biasing schemes prove, in practice, to be very difficult to arrange so that a usable pulse at a single frequency results.

C. Effect of Post Diameter on Performance

Next, a single, large, one-inch post with a one-inch-diameter sphere was mounted on one side only of each capacitor, sparking directly to the neighboring capacitor plate (Fig. 9). This configuration worked very poorly because the gaps no longer fired in synchronism with one another. The discharge was also very uneven because of the non-uniform electric field distribution between sphere and plane. The one-inch-diameter posts were then divided into two posts and mounted symmetrically on each side of every capacitor (Fig. 10). This configuration gave

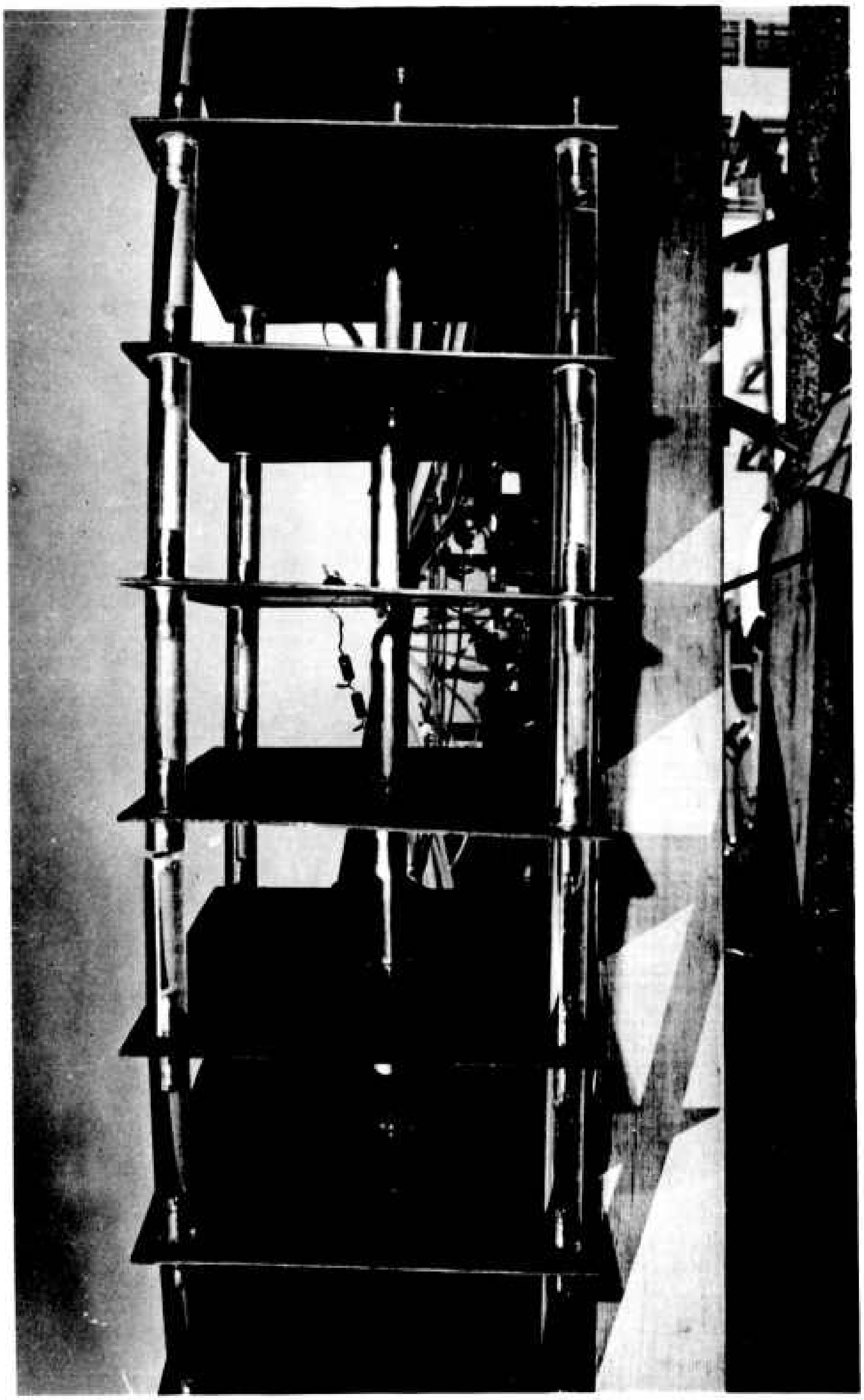


FIG. 9 SINGLE INDUCTANCE POST – 20-Mc TRANSMITTER

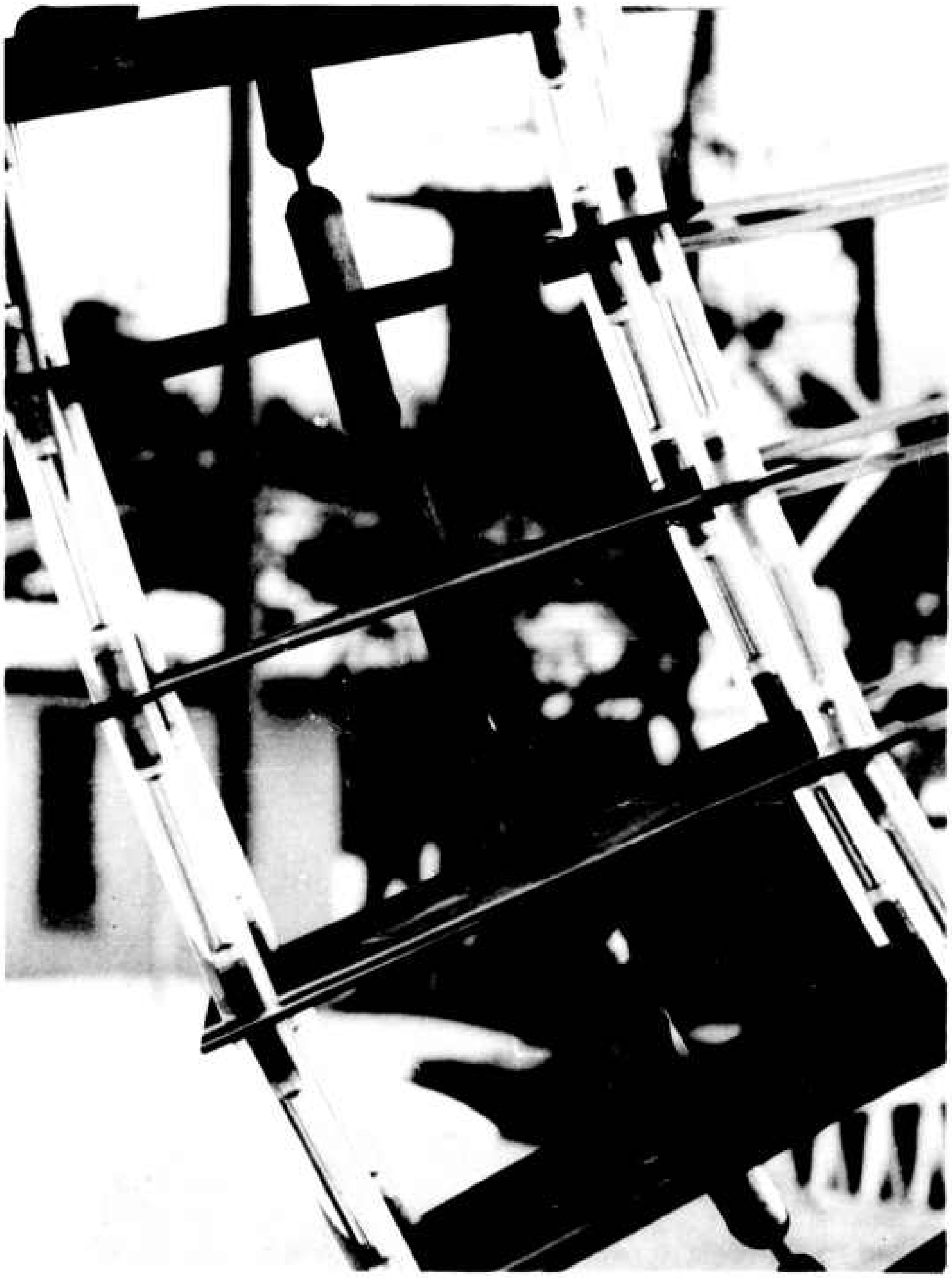


FIG. 10 RING TRANSMITTER WITH DOUBLE 1-INCH POSTS

synchronous operation and removed most of the spurious frequencies. The operating frequency was now found to be 32.5 Mc/s. Weak echoes were again observed at this new frequency, but total peak power was still of the same low order of magnitude.

The secondary ring was fixed in the position of critical coupling in order to lengthen the transmitted pulse. Some improvement in pulse length apparently could be effected in this manner; however, quantitative measurements were not made because of the problem of the low power output.

It was surprising that the output frequency should have shifted from 23.5 to 32.5 Mc when the inductance posts were changed from 1/4-inch to one-inch diameter. Increasing the post size from 1/4 inch to one inch should lower the inductance from 11 to 8.5 μh. This is not enough to account for the observed change in frequency. The fact that radiation was now observed at 32.5 Mc led to the speculation that the individual modules of the oscillator, consisting of capacitor and one post on each plate, were operating as decoupled units. How the individual module oscillators could operate independently from one another, even though coupled at each end to a neighbor through a spark discharge, is difficult to explain. Any irregular firing of the spark gaps, or the presence of high spark-gap impedances, could conceivably cause the modules to operate independently--i.e., operate at the same frequency but not in phase coherence. Each of the 67 modules was built to close tolerances, so that the sum frequency of the 67 oscillators should have a very small bandwidth.

It was discovered that the operating frequency was a sensitive function of the diameter of the conductors which, together with the spark gaps, form the loop of the antenna; in addition, the power spectrum was broad and usually contained one or more secondary maxima which also were sensitive to conductor diameter. In trying to determine the cause of the unsatisfactory power spectrum we considered further the possibility that the unit modules of the ring were self-resonant at frequencies independent of the ring frequency.

In Fig. 11 we show a drawing of a unit or module of the ring. There were 67 such modules used to form the spark-ring transmitter. In this particular configuration the conducting posts, which were mounted on either side of each capacitor, were one inch in diameter, as mentioned before and as shown in the figure. The operating frequency, 32.5 Mc, was the center frequency of the principal maximum of the power spectrum.

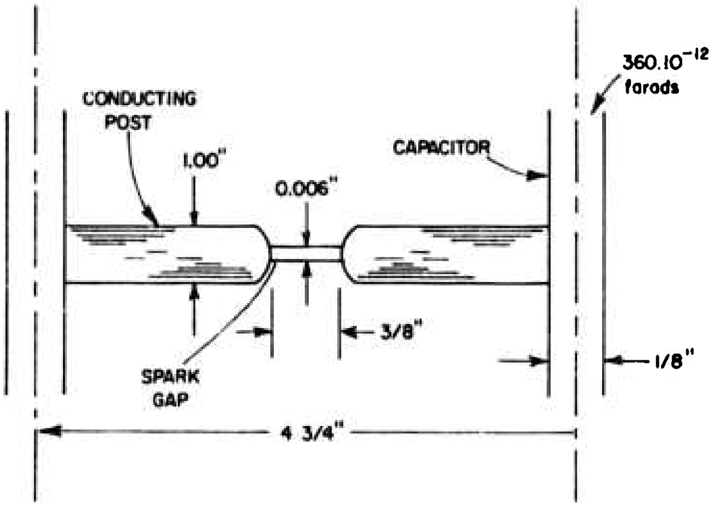


FIG. 11 UNIT MODULE OF THE MARK IV SPARK-RING TRANSMITTER

To calculate the resonant frequency of a unit module, we consider the posts to be straight cylinders. The inductance of a straight cylinder of length ℓ, arising from the external fields, is

$$L_e = 5.08 \cdot 10^{-3}\left(\ell \; 2.303 \log_{10} \frac{4\ell - 1}{d} + \frac{d}{2\ell}\right) \cdot 10^{-6} \text{ henries} \qquad (1)$$

where d is the diameter, and where ℓ is in inches. This formula is plotted in Fig. 12. In the VHF range there is a well developed skin effect and there is no internal field. There is, however, a strong surface field that contributes to the resistance and self-inductance.

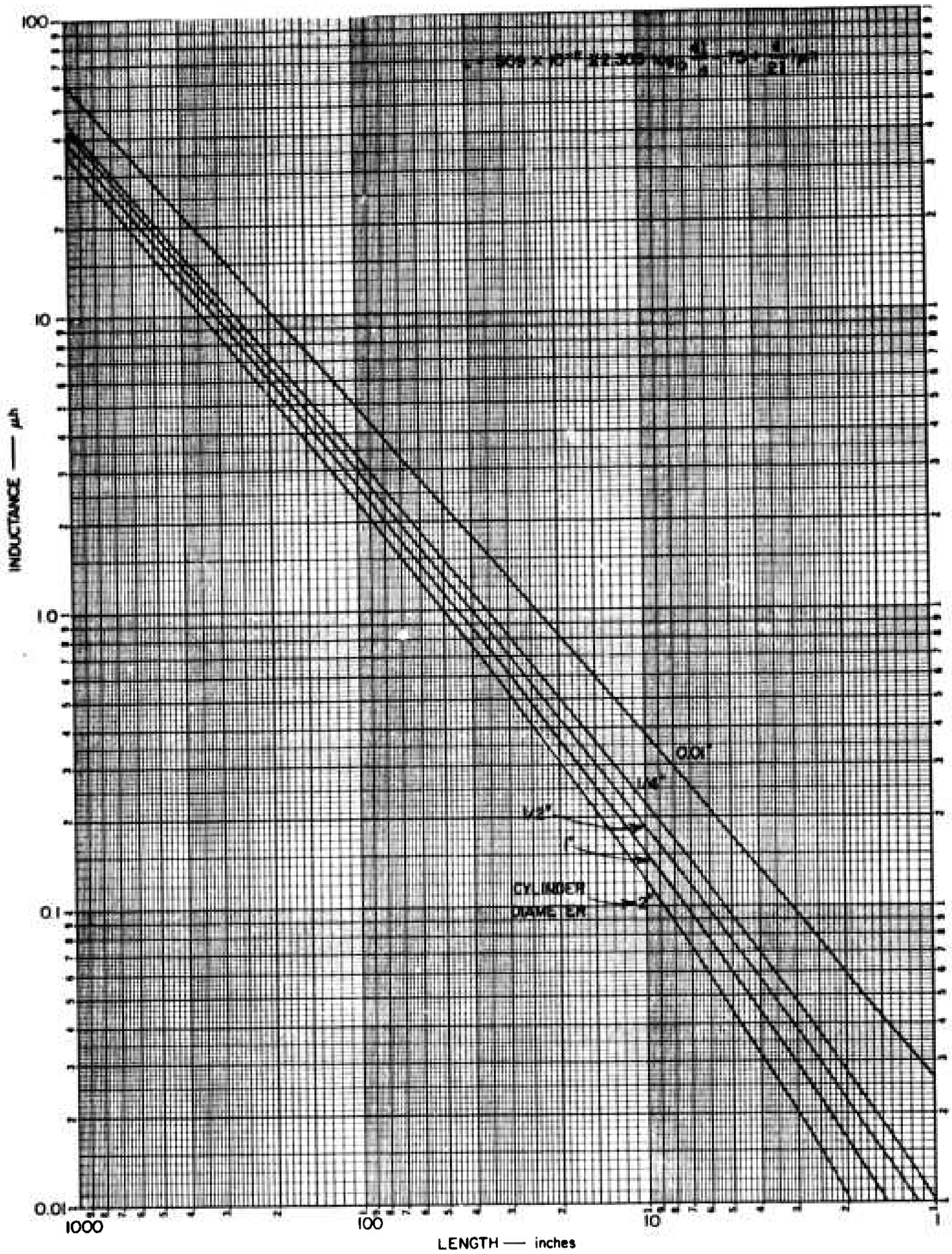


FIG. 12 INDUCTANCE OF CYLINDERS vs. LENGTH

From Stratton,[2] the surface self-inductance is

$$L = \frac{R_o a}{2} \sqrt{\frac{\mu_1 \sigma_1}{2\omega}} \tag{2}$$

where μ_1 is the permeability, σ_1 the conductivity, ω the angular frequency, R_o the dc resistance, and "a" the radius of the cylinder. Since $R_o = 1/\pi a^2 \sigma_1$, we can eliminate σ_1 to obtain

$$L = \frac{1}{2} \sqrt{\frac{\mu_1 R_o}{2\pi\omega}} \quad . \tag{3}$$

The dc resistance is related to the dynamic, or surface, resistance by

$$R_o = \frac{8\pi R^2}{\omega\mu_1} \quad . \tag{4}$$

Combining equations, we find

$$L_s = \frac{R}{\omega} \quad . \tag{5}$$

From the dimensions given in Fig. 11 and from Eq. (1), we find, numerically, $L_e = 4.21 \cdot 10^{-8}$ henries, for the conducting cylinders; and for the spark-gap itself, we find $L_e = 0.864 \cdot 10^{-8}$ henries. To the sum of these we must add also the surface self-inductance, $L_s = R/\omega$.

Let L_e' be the sum of the external inductances for the brass rod and the spark channel; then the resonant angular frequency of the unit module will be

$$\omega_o = [C(L_e' + L_s)]^{-1/2} \quad . \tag{6}$$

Combining Eqs. (5) and (6), we obtain

$$\omega_o = \frac{R}{2L_e'} \left[-1 \pm \sqrt{1 + \frac{4L_e}{R_c^2}} \right] \tag{7}$$

or, numerically,

$$f_o = 1.16 \cdot 10^6 R(-1 + \sqrt{1 + 763/R^2}) \quad ,$$

where f_o is the resonant frequency. In Table II we show resonant frequencies computed for various values of dynamic resistance. The inductive characteristics of a unit module, as functions of dynamic resistance, are given in the third and fourth columns of the same table. Resonant frequency as a function of dynamic resistance also is shown in Fig. 13.

Table II

DYNAMIC RESISTANCE, COMPUTED FROM EQ. (7) AND INDUCTIVE CHARACTERISTICS OF A UNIT MODULE OF THE MARK IV SPARK-RING TRANSMITTER

DYNAMIC RESISTANCE, R_I (ohms)	RESONANT FREQUENCY f_0(Mc)	SURFACE INDUCTANCE L_s (henries) x 10^{-8}	RATIO OF SPARK CHANNEL INDUCTANCE TO TOTAL INDUCTANCE, L (spark)/L (rod + spark)
0.1	38.4 Mc	0.0415	0.177
0.5	37.4	0.212	0.204
1	36.9	0.431	0.236
2	35.4	0.877	0.293
3	33.9	1.41	0.350
5	31.2	2.55	0.448
10	25.6	6.21	0.626

It can be seen from Fig. 13, as well as from Table II, that our measurement of a resonant frequency of 32.5 Mc not only serves to identify the source of the resonant frequency, but also constitutes a measurement of the dynamic resistance of the spark gap. From Fig. 13 we see that the observed frequency of 32.5 Mc corresponds to a resistance

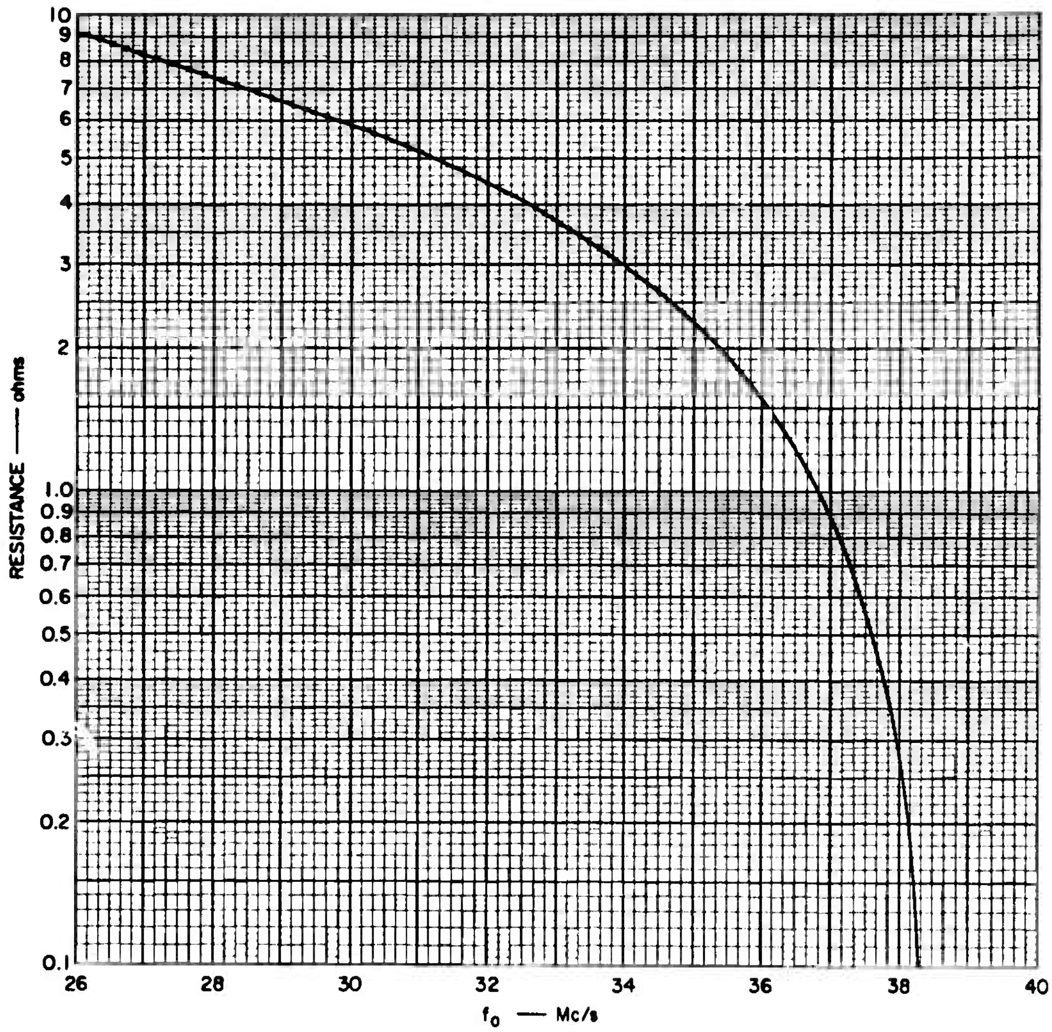


FIG. 13 RESONANT FREQUENCY vs. SPARK GAP DYNAMIC RESISTANCE

of about 4 ohms per spark-gap. This large a resistance implies that the spark ring cannot work at better than about 8-1/2 percent efficiency. There is probably considerable error in this calculation of the dynamic spark resistance, one of the sources of error being in our estimate of the effective spark channel at 0.006 inch. By measuring the logarithmic decrement of spark-discharge oscillations, as recorded on oscilloscope photographs, we can use the formula

$$R = \frac{\omega L}{\pi f t} \log_e 2 \tag{8}$$

to compute the dynamic resistance. Measurements made on a single unit module give a dynamic resistance of about 1.3 ohms, which indicates that our estimate of spark-channel diameter was too small.

Having found an agreement between the observed and the computed module frequency, we considered next why the ring resonates at the module frequency. The external inductance of a loop is approximately

$$L_o = 0.0320\ a \left(2.303 \log_{10} \frac{16a}{d} - 2\right) \cdot 10^{-6} \text{ henries} \tag{9}$$

where a is the radius, in cm, of the loop. If we substitute $\ell = 2\pi a$ into Eq. (1), we see that it becomes almost equal to Eq. (9), except for a factor of $\pi/2$ in the argument of the logarithm and a change in the corrective term of -1 or -2. These differences are not appreciable, however.

The principal reason for the difference in theoretical and operating frequencies derives from the fact, in the case of inductance, that the whole is not equal to the sum of its parts. If we compute the inductance of one module of the ring, using Eq. (1), and multiply the result by the number of modules, we get $(4.21 \cdot 10^{-8})(67) = 2.82 \cdot 10^{-6}$ henries. If we compute the inductance of the ring by Eq. (8) we get $8.8 \cdot 10^{-6}$ henries. The difference derives from the argument of the logarithm: multiplying by 67 does not comprise a corresponding increase in the length-to-diameter ratio in the argument of the logarithm. The formula for loop inductance includes mutual inductances not present in the analysis of a single module.

Since the operating frequency is predicted closely when inductance is calculated for a unit module from Eq. (1), we are led to consider the possibility that the unit module determines the operating frequency of a spark transmitter. Unfortunately, ring designs in the past have been based on the loop inductance as given by Eq. (9), (see Fig. 14).

Since the module frequency may determine the transmitter frequency, and since the observed power spectra usually included one or more unwanted harmonics, we have considered the possibility that the interaction of module and loop or ring resonances was the cause of harmonics and power loss. We can ask that the ring inductance be equal to module inductance, multipled by n, the number of modules in the ring, a condition that should make both frequencies equal and eliminate harmonics. Multiplying the right-hand side of Eq. (1) by n and equating it to the right-hand side of Eq. (9), we obtain $a = 0.68\ell$, or the circumference of the ring is equal to 4.27ℓ. This result, indicating that only four unit modules can be incorporated into the ring, is probably spuriously based on the approximations in the theoretical equations for inductance; nonetheless, it indicates the impracticability of equating unit and ring resonances.

We subsequently attempted to equate ring and module resonances by deforming the perimeter of the ring. In Fig. 15 we show the "panhandle" configuration, in which the ring was reduced in diameter and the left-over portion of the original perimeter was formed into a shorted transmission line introduced at one point in the ring. This configuration was devised in an attempt to reduce the inductance of the ring without reducing the number of unit modules. Testing of this configuration was unsatisfactory. Apparently the mismatch at the junction of pan and handle was sufficient to cause each to resonate independently. Attempts to reduce the mismatch by tapering the transmission line were unsuccessful because the resultant configuration resembled the original ring in contour and performance.

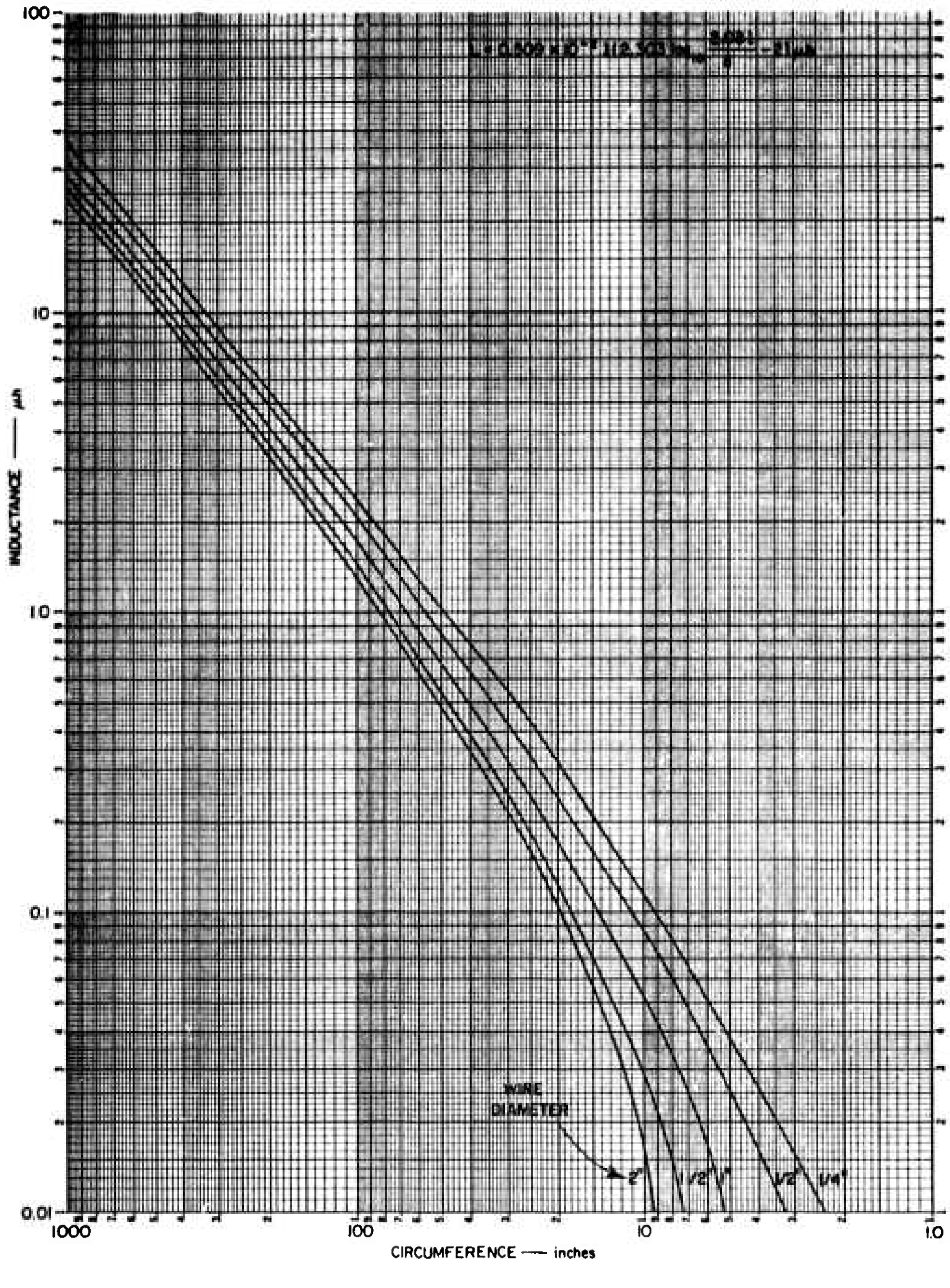


FIG. 14 INDUCTANCE OF CIRCULAR LOOPS vs. CIRCUMFERENCE

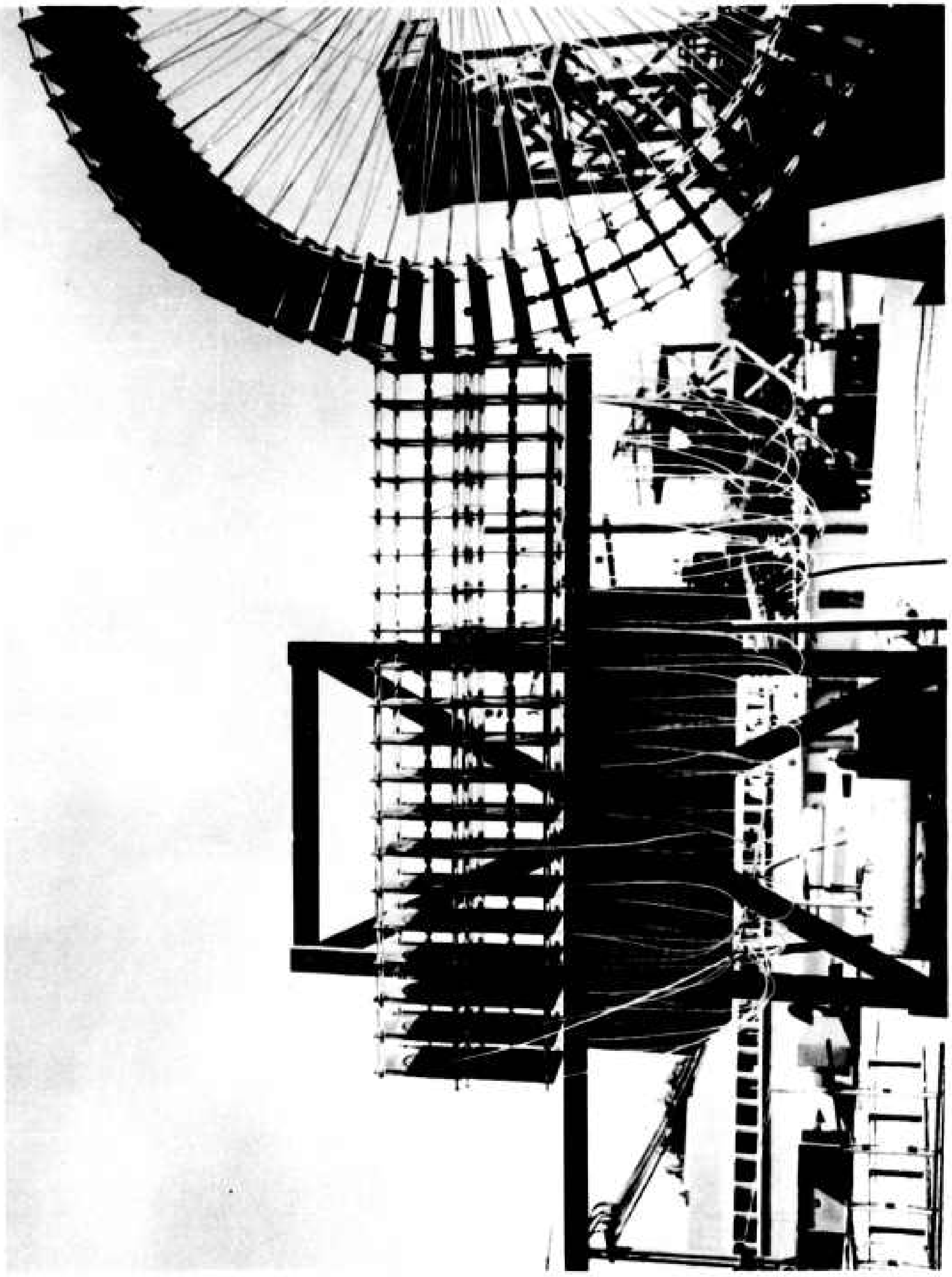


FIG. 15 RING TRANSMITTER WITH PANHANDLE

D. Radial Wire Transmission Lines

Discussions with Dr. Landecker during his recent visit to SRI resulted in his general concurrence with our previous findings concerning the use of transmission lines to connect the individual modules to a central spark gap in the manner illustrated in Fig. 16. He also had tried this scheme and found that transmission line losses and unwanted modes presented major problems. However, he described an alternate arrangement in which he used air-dielectric, open-wire lines in a novel configuration (Fig. 17). Two shorted turns were used to establish equipotential rings on each side of the capacitors. These rings are connected to the center of the ring by radial wires which, with their opposing members, form open-wire transmission lines with impedances of approximately 600 to 700 ohms. A ring transmitter with radial wires of this type installed is shown in Fig. 18. The individual capacitors were connected to the shorted rings as shown in Fig. 19. The total length of the radial wire line is made equal to a half-wavelength by adding a folded section along the axis of the ring at the center. A shorting of the far end of the radial lines by a spark, or switch, transfers a short across the two equipotential rings. When this occurs, currents flowing between the two shorting rings will not radiate because of the low radiation resistance and the partial cancellation of the currents; however, the tangential currents that flow in and out of the capacitors will radiate.

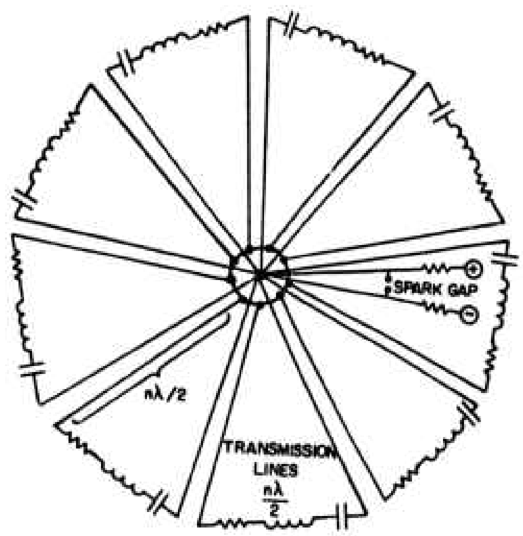


FIG. 16 RING TRANSMITTER WITH SINGLE, CENTRAL SPARK-GAP

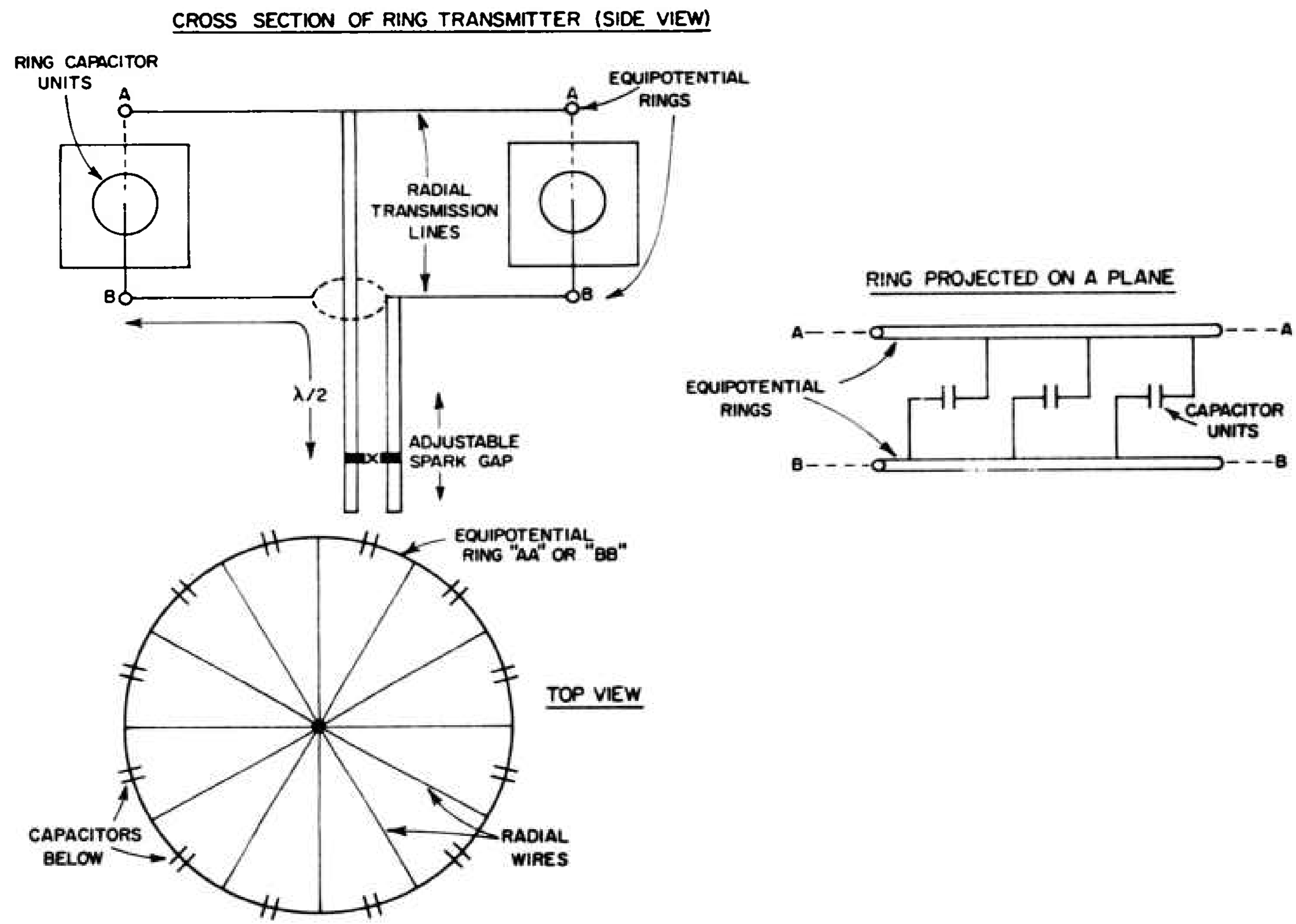


FIG. 17 RADIAL TRANSMISSION LINE SCHEME

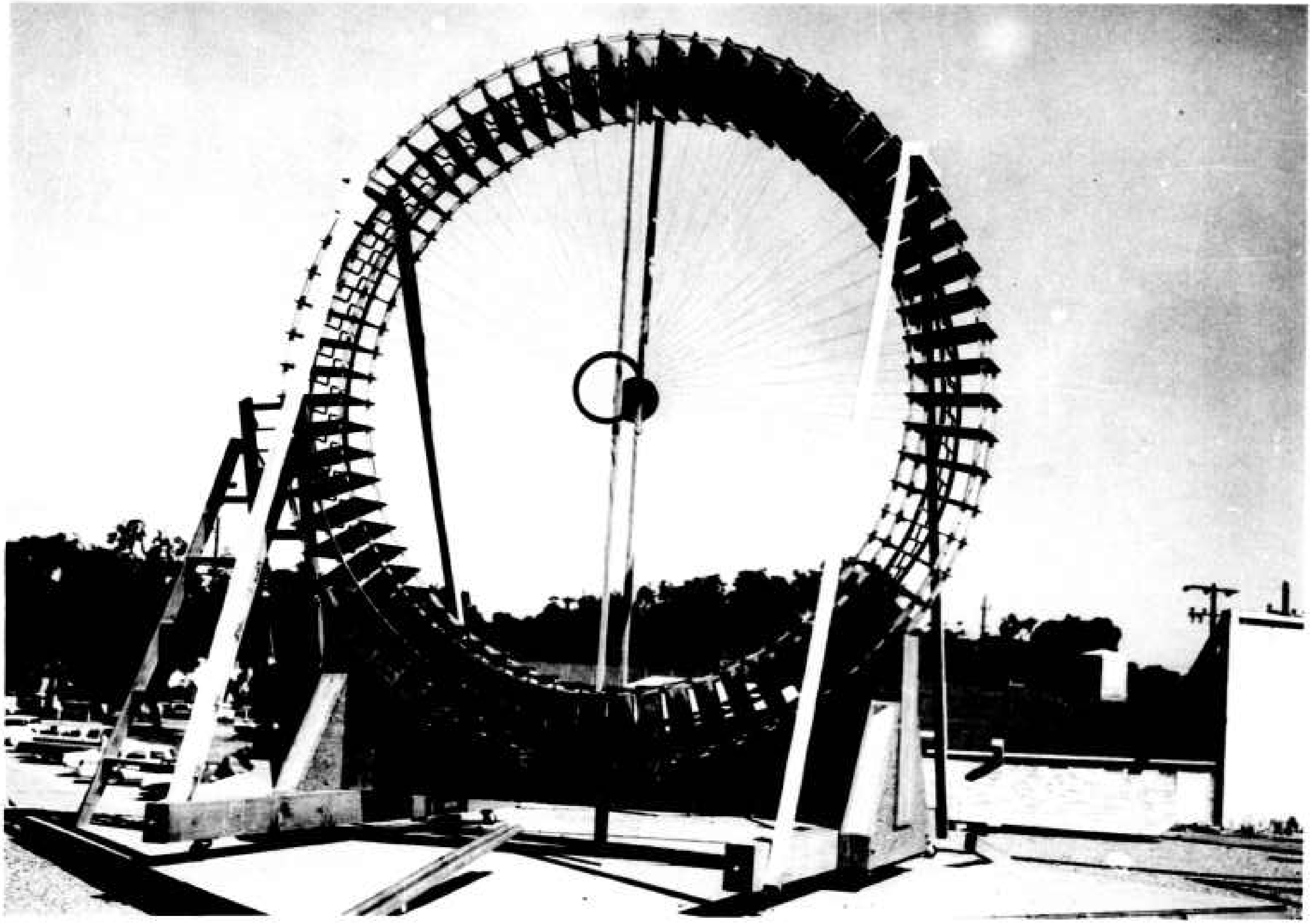


FIG. 18 RING TRANSMITTER WITH RADIAL WIRE TRANSMISSION LINES

FIG. 19 DETAIL SHOWING EQUIPOTENTIAL RINGS ON RING TRANSMITTER

The impedance at the junction of the radial lines in the center of the ring is of the order of ten ohms. The transmission line should be extended axially from this point, in 10-ohm line, until the total length is a half wavelength at the frequency of the individual ring modules. Landecker found that small adjustments of this line length could be used as an effective means of tuning the transmitter frequency.

Figure 20 shows the Mark IV ring with radial lines and a 10-ohm air-dielectric, coaxial line. The new operating frequency was found to be 17.5 Mc. This configuration was found to radiate very little power at the desired frequency, most of the stored energy being lost in the transmission lines and in unwanted circulating currents. A conventional spark gap across the end of the 10-ohm line was used first; subsequently, it was replaced by an ignitron, General Electric Type 7703, in an attempt to eliminate spark-gap losses. The use of an ignitron did not significantly change the results.

Another configuration was tried in which the shorting circular rings were removed (AA and BB in Fig. 17), so that each of the radial wire transmission lines was connected to one individual module. With either the ignitron on a conventional spark shorting the remote end of the 10-ohm line, the radiated pulse from the system was observed to be very weak. Spurious modes associated with the ringing of the transmission lines were also noted.

Analysis of the transmitter and associated lines shows that even a very good short at the end of the 10-ohm line appears across each module as a resistance large compared to the radiation resistance of the module. Thus this method does not effectively short-circuit each module. A good short is required if high powers are to be generated. It appears that it is not possible to effectively short the end of the 10-ohm line either with a conventional spark or with an ignitron. In either case the losses, which may be only a fraction of an ohm, and the poor geometry of the short make it difficult or impossible to short each module as required. Considerable care was taken in the arrangement of the spark gap and ignitron at the end of the 10-ohm line; however, good performance could not be achieved.

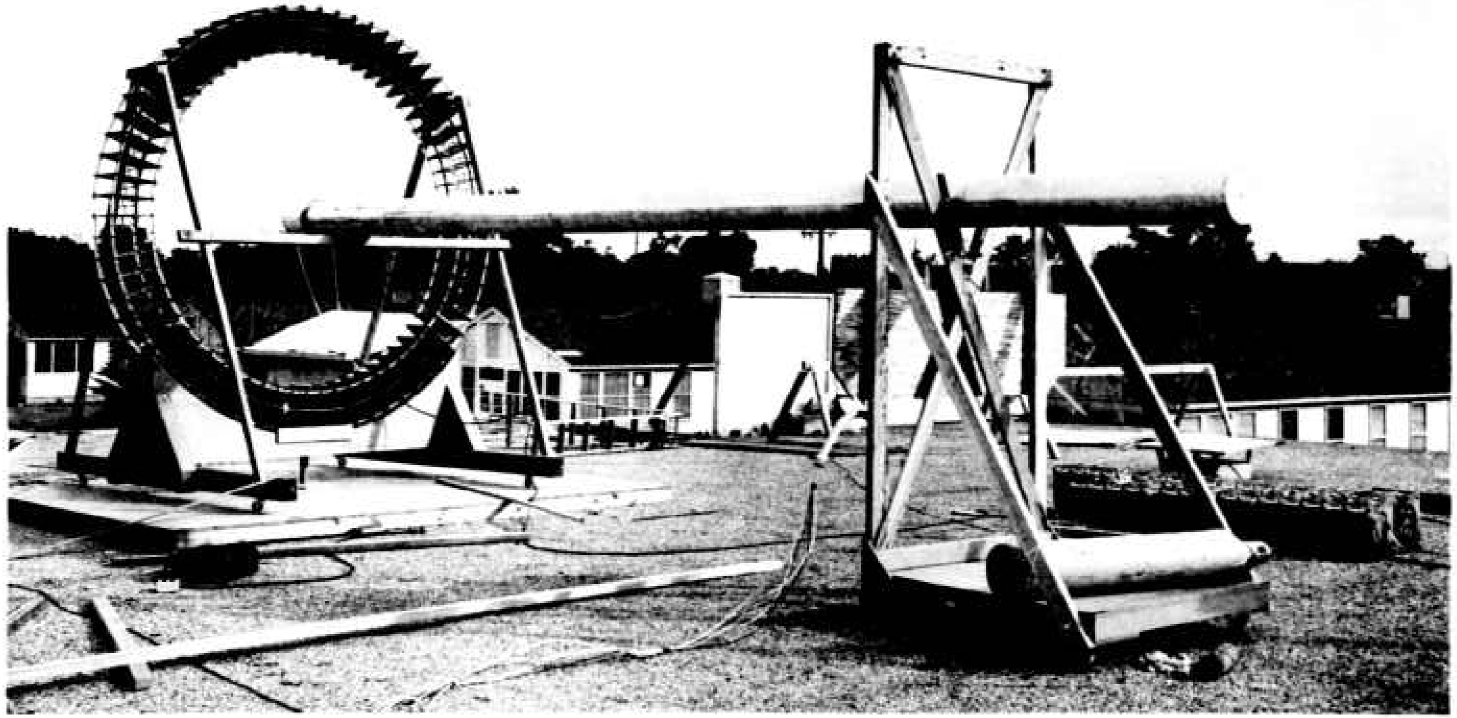


FIG. 20 MARK IV RING WITH 10-ohm LINE

We conclude that the radial wire transmission line scheme, though the series line losses are low due to the air dielectric, cannot be used effectively unless an extremely low impedance short can be physically realized at the remote end.

E. Parasitic Elements

During the past reporting period one of the smaller spark-ring transmitters, shown in Fig. 21, was used as the exciting element of a Yagi array. The purposes of this experiment were to determine the feasibility of constructing directive, end-fire arrays using ring transmitters and to study the coherency and power spectrum of the radiated energy.

The exciting element of the array was a 470-Mc spark-ring transmitter, mounted coplanar with the passive director and reflector elements. In Fig. 22 we show the spacings and dimensions of the four director and two reflector elements. The spacings were determined experimentally, and the other dimensions were taken from a standard Yagi design. Figure 23 is a photograph of the antenna taken during the course of radiation pattern measurements.

Radiation pattern measurements were obtained by rotating the array, on the roof of the laboratory building, and receiving the signal with a broadband, logarithmically periodic antenna (Fig. 24). The receiving antenna was matched to a crystal detector and the power output was observed with a tuned amplifier. Angular measurements were made point-by-point, and the observed radiation pattern is shown in Fig. 25. Power measurements were made in the H-plane only, and the E-plane pattern was estimated from theory. Measurements were difficult and time-consuming because of the unstable repetition rate of the transmitter. The repetition rate of the transmitter is supposed to be equal to the frequency of the tuned amplifier, 1000 cps. This high a repetition rate was difficult to achieve in a stable manner with the spark-ring transmitter. We subsequently obtained a modified 315-cps amplifier and plan to repeat the measurements.

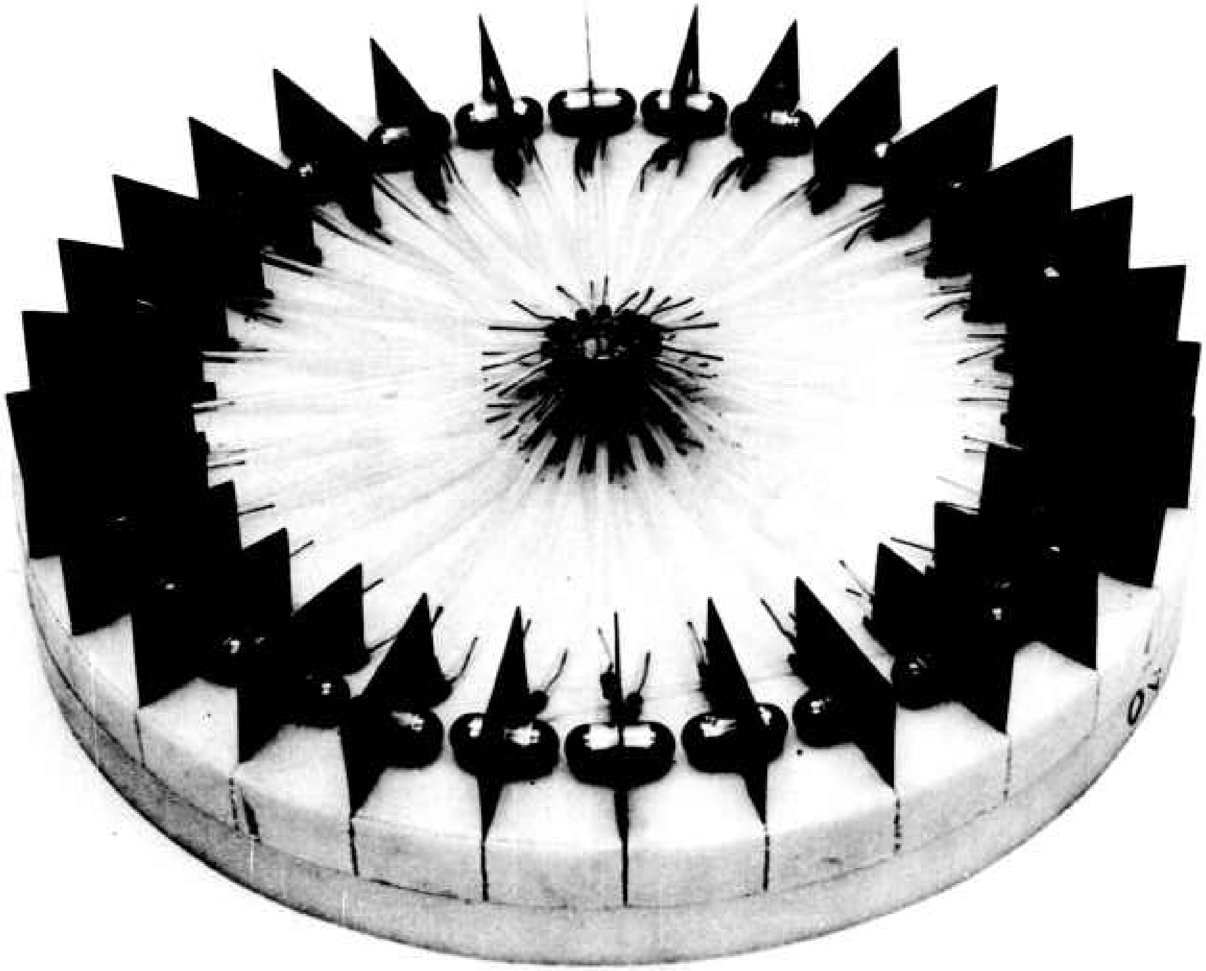


FIG. 21 SMALL UHF RING TRANSMITTER

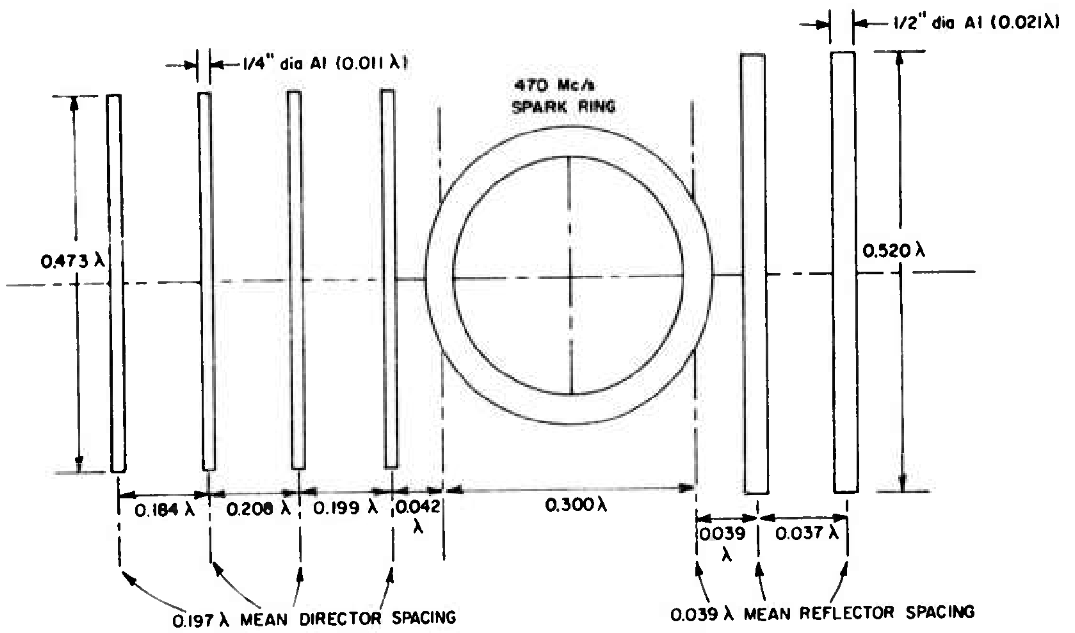


FIG. 22 SMALL RING WITH PARASITIC ELEMENTS

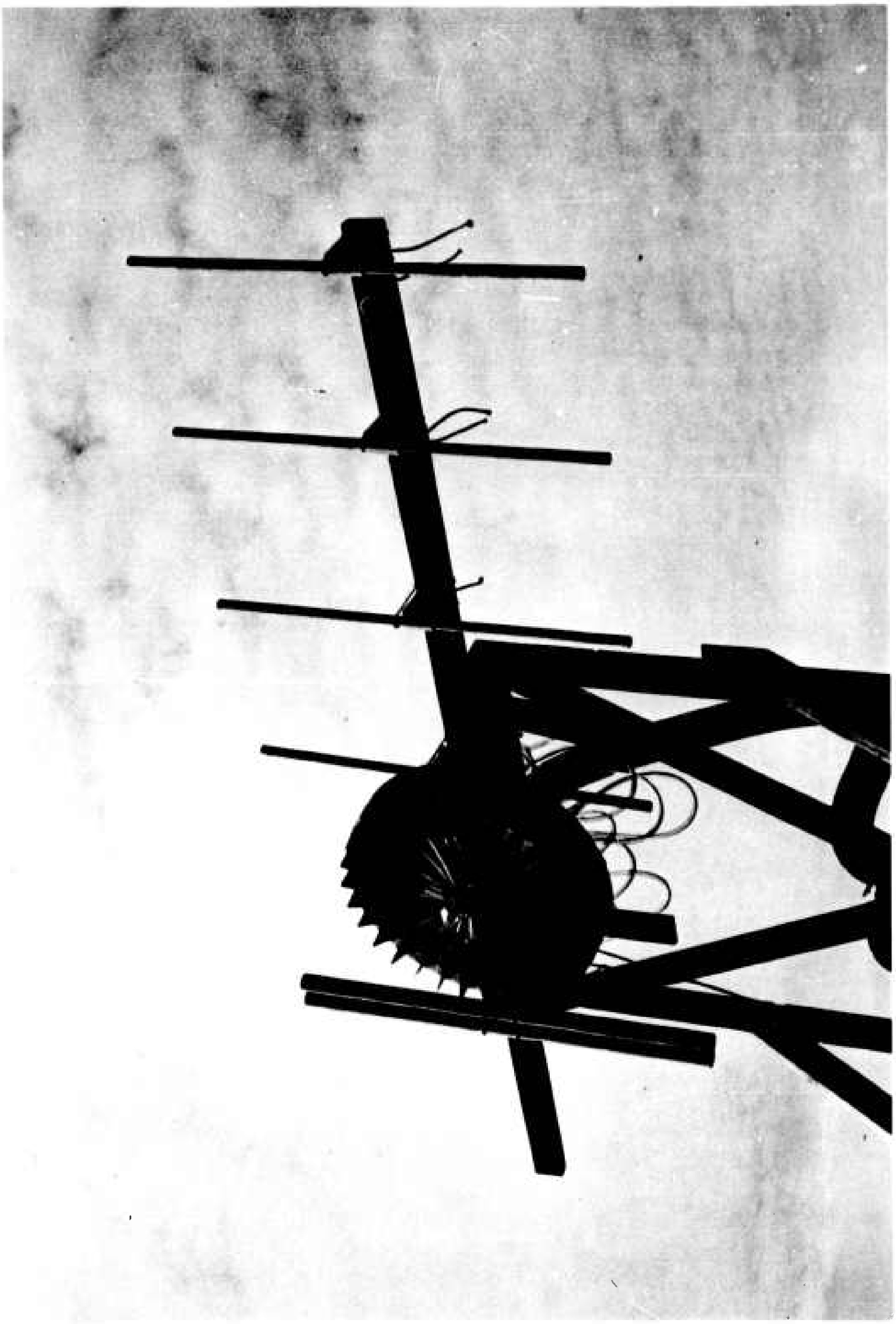


FIG. 23 UHF RING DURING PATTERN MEASUREMENTS

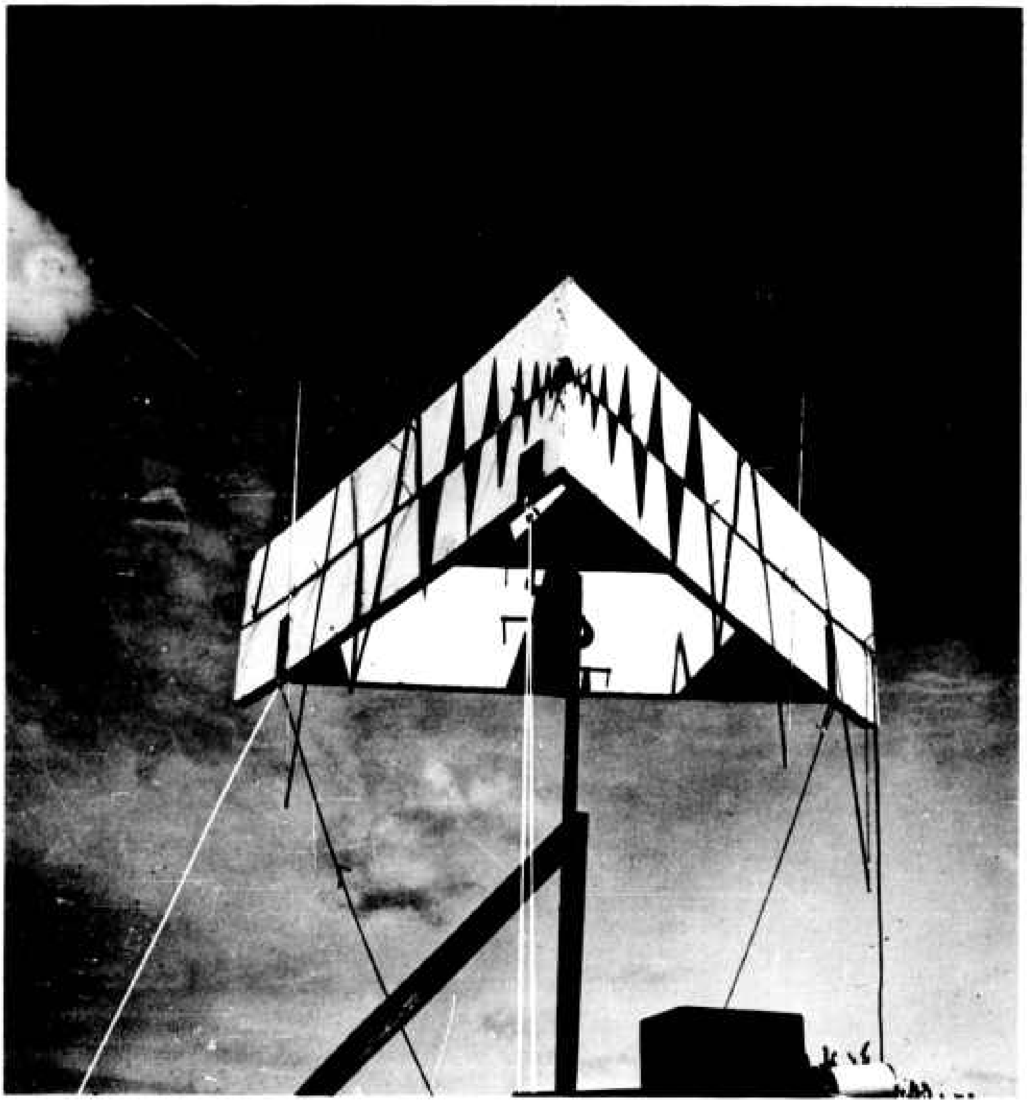


FIG. 24 RECEIVING ANTENNA FOR PATTERN MEASUREMENTS

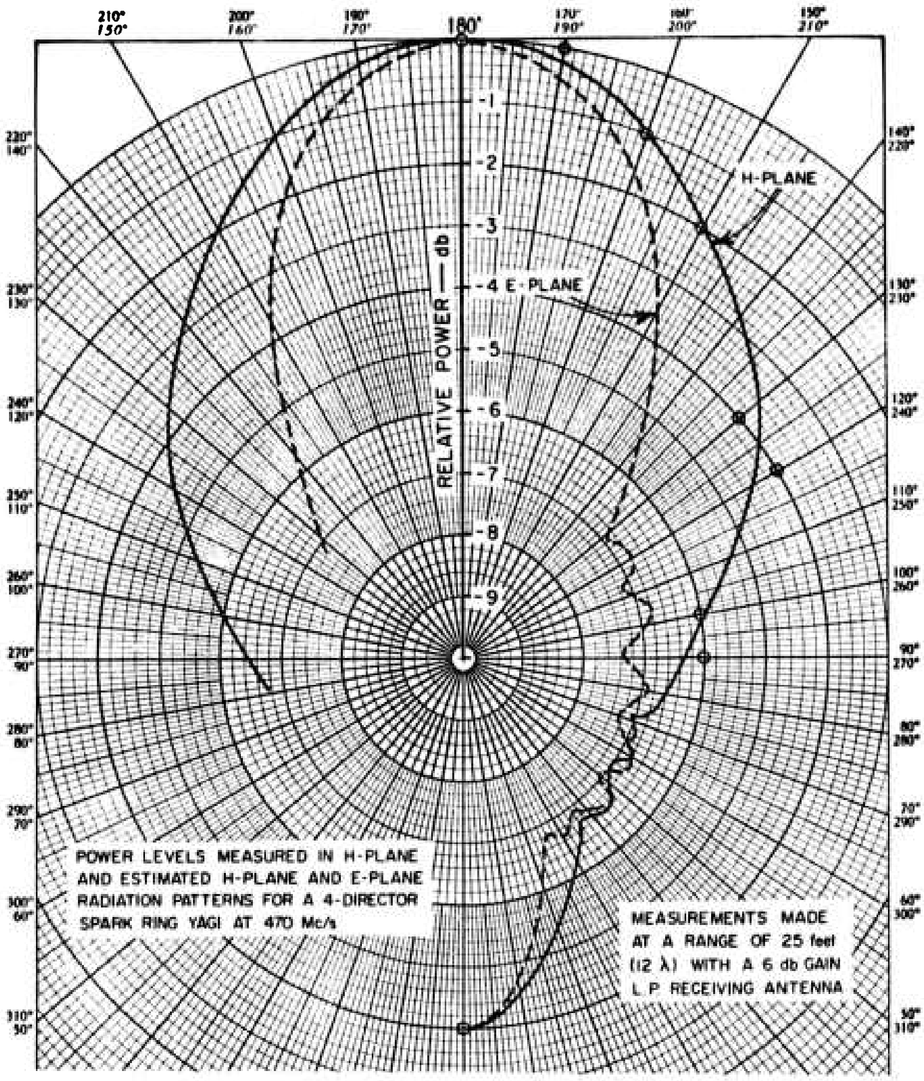


FIG. 25 ANTENNA PATTERN – SMALL RING WITH PARASITIC ELEMENTS

The results of the pattern measurements indicate that there is no difficulty in efficiently coupling a spark-ring source into a unidirectional, end-fire array. Inefficiencies appear to be those in the spark ring itself, not the array performance. The fact that the directivity of the array is not much less than optimum indicates that radiation coherency is maintained over at least 2-1/2 wavelengths, at a frequency of 470 Mc. From the pattern measurements we can conclude that the portion of the coherent power spectrum close enough to 470 Mc to be directed by the 5-element array contains at least about 13 percent of the total RF power generated. We estimate that frequencies within ±30 percent of 470 Mc would be directed by the array; therefore, at least 13 percent of the total, coherent, radio power is contained in 330-to-610-Mc frequency band. By building longer arrays and determining the point at which additional array elements do not result in additional directivity, one should be able to determine the coherence length and coherent power spectrum of spark-ring transmitters.

There is some indication that the radiation coherence of the 470-Mc ring transmitter may not be much better than the lower limit estimated above. Prior to the construction of the array, several radiation measurements were made of the ring transmitter itself, and it was observed that radiation power in the axial direction was only a few decibels less than the power radiated in radial directions.

A small loop, excited at one point from a transmission line, radiates only in the radial direction. If the loop is made larger, additional lobes will appear in the radiation pattern in directions out of the plane of the loop; however, there will always be a null in the axial direction. The only conventional way of achieving the phase distribution required for axial radiation is to break the loop and excite it at one end as, for example, a single-turn helix excited over a ground plane. Under these conditions, and for a limited range of frequencies, the loop will radiate in the axial mode.[3]

If we assume that a considerable portion of the RF energy in the ring is incoherent, then we can conclude that a novel excitation of the

axial mode can occur. If a portion of the energy contains a random distribution of phases, then such energy will excite the axial as well as the radial mode. Since the sub-portion that excites a radial mode is incoherent, and since there may also be a coherent portion in the radial mode, we should expect a broadening of the radial beam, as well as the appearance of an axial beam. We may conclude that one possible explanation of the appearance of an axial beam is that a considerable portion--perhaps 1/4 to 1/2 of the RF power--is incoherent. Such incoherency probably derives from a lack of synchronization of the spark-gap discharges.

III EXPERIMENTS WITH SMALL DRIVER RINGS

Full-size ring spark transmitters are designed so that antenna and transmitter are one unit, with radiation resistance comprising the dissipative element. An alternate scheme is to use small rings that can be coupled to separate antennas. The use of barium titanate and ceramic capacitors makes it possible to store large amounts of energy in small rings. Landecker has described small driver rings that can be connected to full-scale rings as shown in Fig. 26. To ascertain the

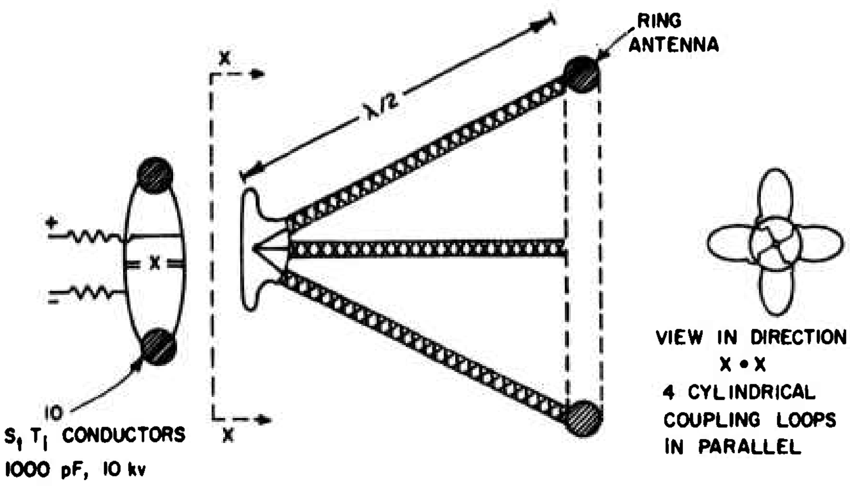


FIG. 26 LANDECKER DRIVER OSCILLATOR COUPLED TO FULL-SCALE RING

the performance of driver rings, several models were built and tested. In Fig. 27 we show a very simple ring made in an hour's time using standard components. This unit produced incoherent oscillations, presumably because its capacitors varied as much as 20 percent. This ring also was operated from a single central spark gap with the capacitors connected by short lines. The resultant pulse remained incoherent.

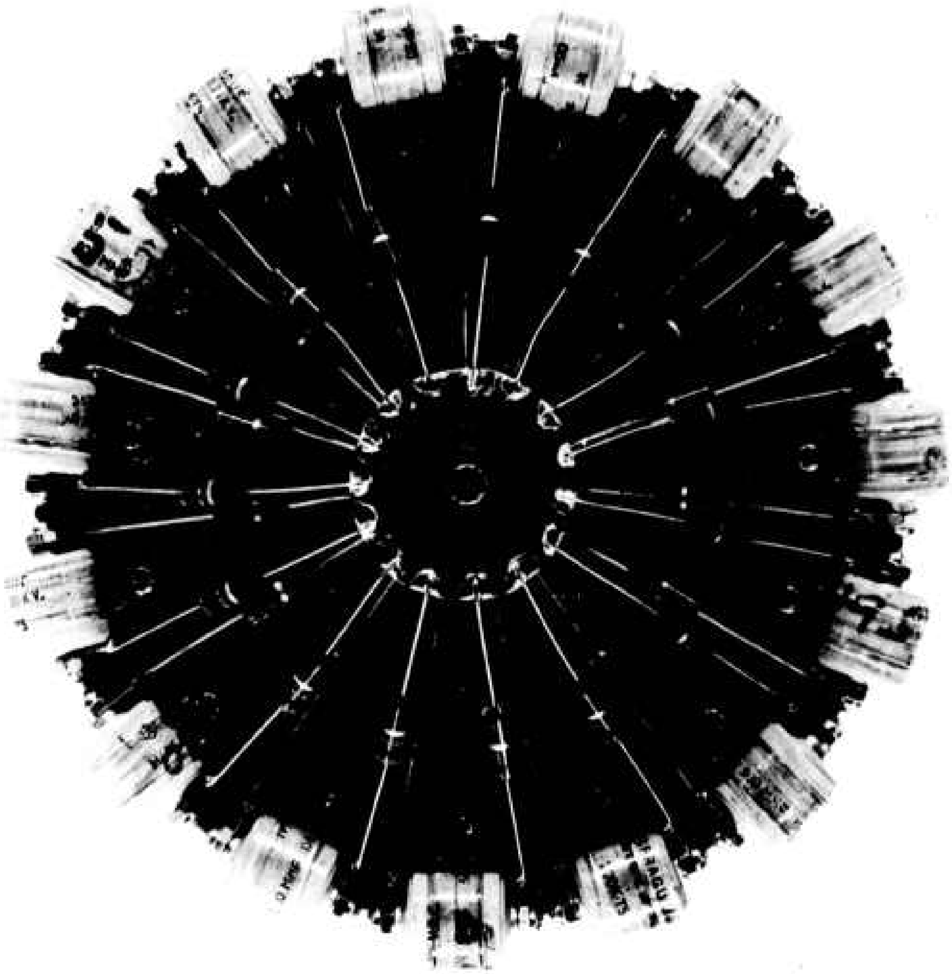


FIG. 27 SIMPLE DRIVER RING

A second model was constructed in which the capacitors were made from printed circuit board laminate that could be cut to closer tolerance. This unit operates at about 15 Mc (Fig. 28). However the observed pulse was only a few tenths of a microsecond long and was highly irregular and incoherent. Evidently the short transmission lines connecting the individual capacitors to the center spark gap operate as independent oscillators, not as short connecting transmission lines, and the oscillations in the ring do not become coherent and in phase with one another. Attempts to improve this ring were unsuccessful.

Another small driver ring is currently under test in the laboratory. The capacitors in this ring are standard 150-pf vacuum capacitors. Experiments with small driver rings are continuing and will be fully reported in the final report. There is some hope that good operation and reasonable power levels can be achieved.

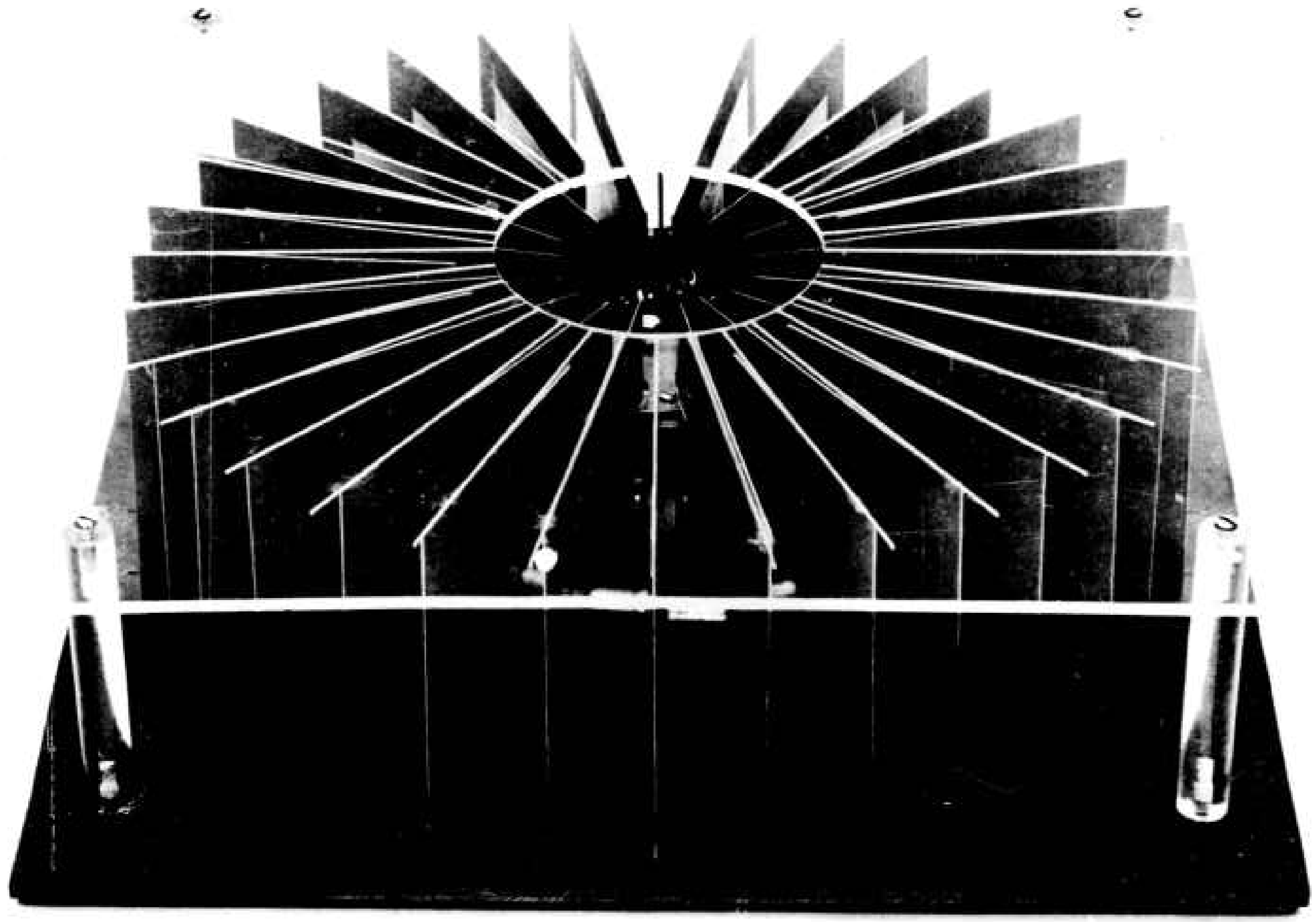


FIG. 28 DRIVER RING USING COPPER-CLAD LAMINATE

IV FERRITE FREQUENCY MULTIPLIERS

The commercial availability of ferro-ceramic materials (Fig. 29) having good characteristics in the HF and VHF range, leads to the possibility that ferrite devices can be used to generate high-power RF pulses by multiplying the frequency of a low-frequency spark discharge. Since it is easy to generate very high peak powers and long pulses at low frequencies of the order of 1 Mc, ferrite devices could be used to generate harmonics at higher power levels and frequencies. Such schemes have been proposed by Landecker (Fig. 30) and by W. Millar (Figs. 31 and 32).

In our laboratory a 1.6-Mc driver circuit, made of high-Q polystyrene capacitors, was used to study harmonic generation with ferrites. A conventional spark-gap, a quenched gap, and an ignitron were used to discharge these capacitors through a one-turn coil. The conventional spark gap gave a better wave-form, and nearly the same Q, as the ignitron. The quenched gap, used with a 1.6-Mc gapless secondary circuit, showed that rapid quenching of the primary, and subsequent free oscillation of the secondary, resulted in a longer pulse. In Fig. 33 we show the pulse generated by discharging a 0.06-μf capacitor, with a Q of 150 and charged to 20 kv, through the one-turn inductor. Also shown are various harmonics obtained by coupling a tuned secondary to the driver ring through a bundle of ferrite rods. The secondary circuit was tuned to the harmonic desired. Power output was measured by a directional coupler connected across a dummy load. This experiment verifies and confirms the work of W. Millar, indicating that powers of the order of 1 Mw and pulse widths of the order of 50 μsec can be generated by this method. The upper frequency limit is about 30 Mc because it is difficult to build high capacitances with low internal inductance. Smaller capacitance reduces the energy storage so rapidly that the technique is best suited for frequencies from 1 to 15 Mc. To achieve a higher power, the capacitors should be charged to a higher potential, since the peak power

is proportional to the square of the voltage. To increase the pulse length and average power, the capacitor quality, Q, should be as high as possible. The efficiency of harmonic generation can be improved by use of a toroidal-core ferrite material for the transformer. W. Millar reports an efficiency of 70 percent in generating the fifth harmonic.

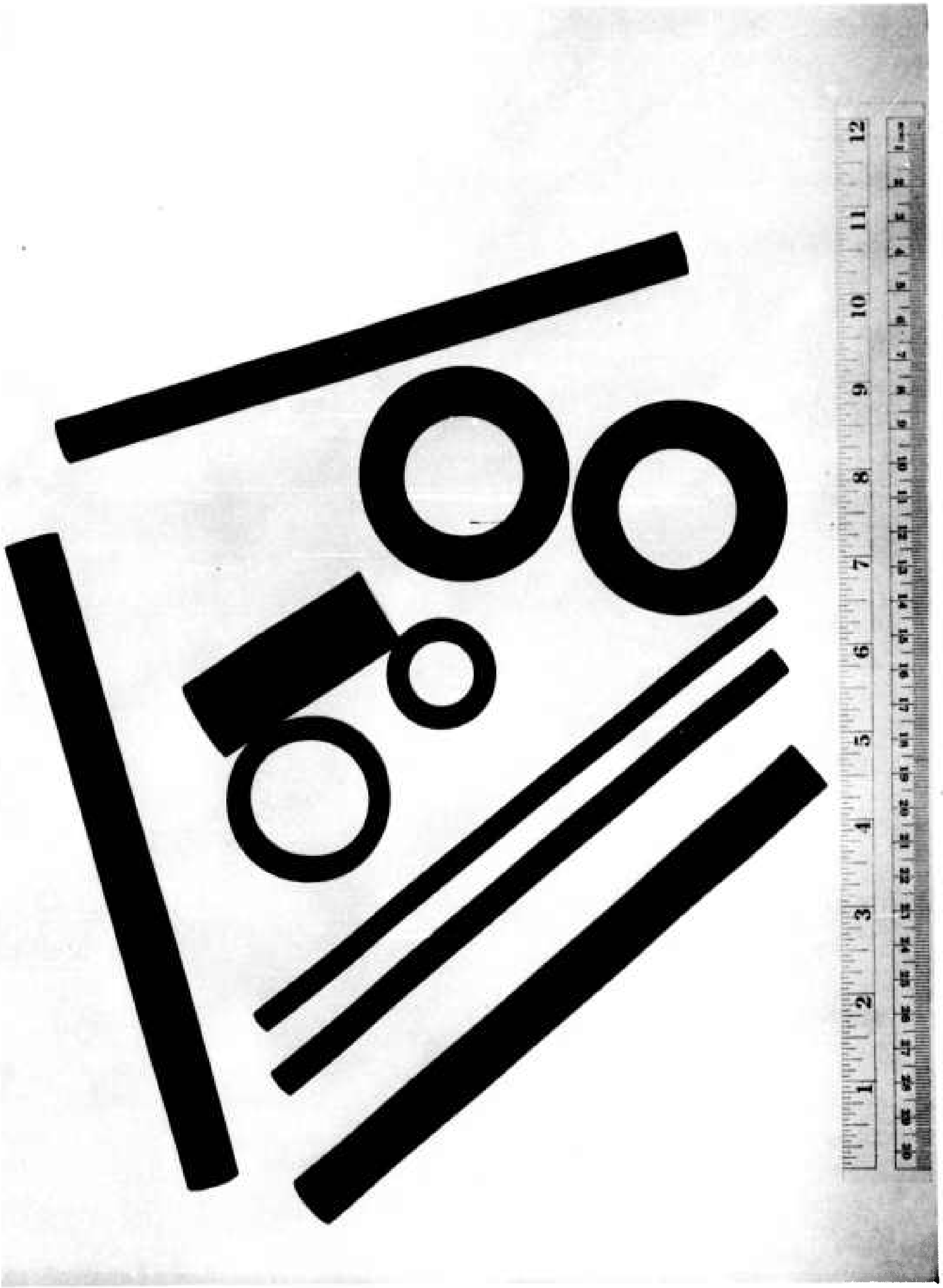


FIG. 29 COMMERCIAL FERRO-CERAMIC MATERIALS

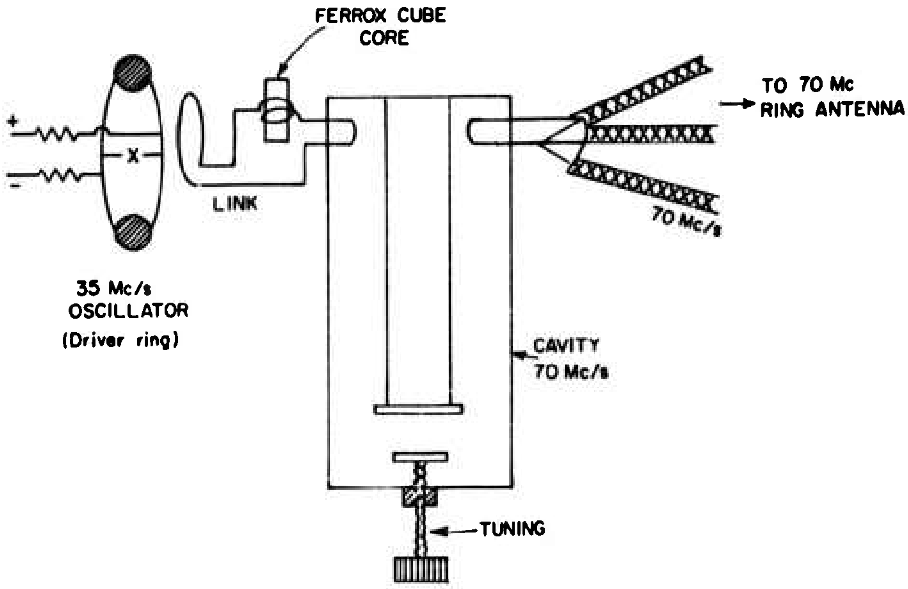
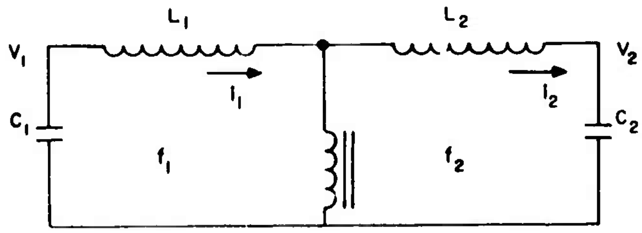


FIG. 30 LANDECKER FREQUENCY MULTIPLIER FOR 70-Mc TRANSMITTER



$f_2 \doteqdot n f_1,\ n = 1, 3, 5, 7, \cdots$

$L_1 \ll L_2$

$i_1 \geq n i_2$

ΔV_2 (increase in amplitude every $\frac{n}{2}$ cycles) $\leq 2V_1$

Q_1 (circuit loss only) $\doteqdot 2n^2$ FOR 50 % EFFICIENCY

SO WANT $Q_1 \gg 2n^2$ IF POSSIBLE

THE SATURATING CHOKE CAN BE REPLACED BY A TRANSFORMER PERMITTING IMPEDANCE TRANSFORMATIONS

FIG. 31 BASIC FERRITE FREQUENCY MULTIPLIER

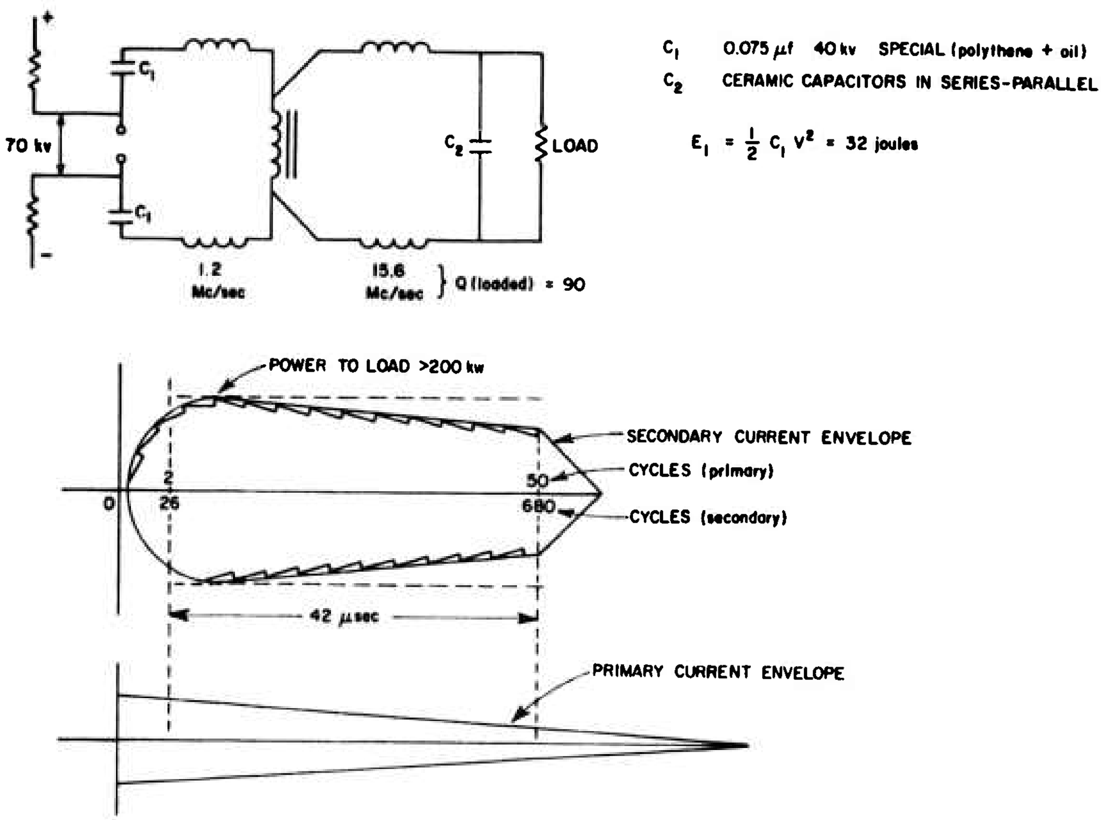


FIG. 32 FERRITE FREQUENCY MULTIPLIER CIRCUIT

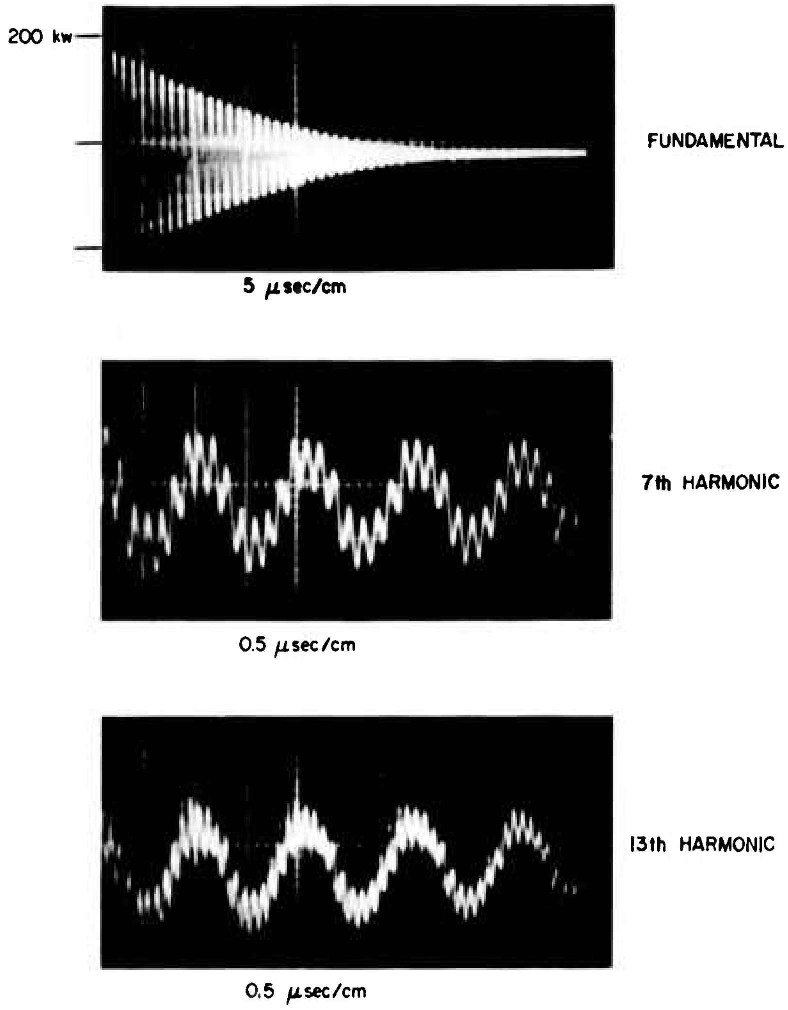


FIG. 33 FERRITE FREQUENCY MULTIPLIER WAVEFORMS

V UNIT OSCILLATORS

The use of small unit oscillators coupled directly to a dipole antenna has been considered from the beginning of this project. Landecker describes a 38-Mc unit oscillator consisting of a stack of barium titanate capacitors immersed in oil [Fig. 34(a)]. Landecker reports obtaining a peak-power of 500 kw with a usable pulse of about one-half microsecond from a charging voltage of 25 kv. The dielectric strength and oil insulation would permit operation of this oscillator at voltages as high as 100 to 250 kv, which would increase the power output 10 to 100 fold. Figure 34(b) shows a variation on the original configuration. Figure 35 is a photograph of a similar oscillator built at SRI which is currently under test. Difficulties have been experienced in obtaining useful RF pulses from the barium titanate capacitors available.

The possibility of building an array consisting of unit oscillators and their associated dipoles, has also been contemplated previously. Since two unit oscillators placed a fraction of a wavelength apart readily synchronize and yield a single coherent pulse, such pulse being twice the amplitude of one oscillator, there is a possibility that an array of oscillators would lock together in synchronous, coherent radiation. Laboratory experiments have shown also that the presence of a few hundred volts of CW across a spark gap assists gap synchronization.

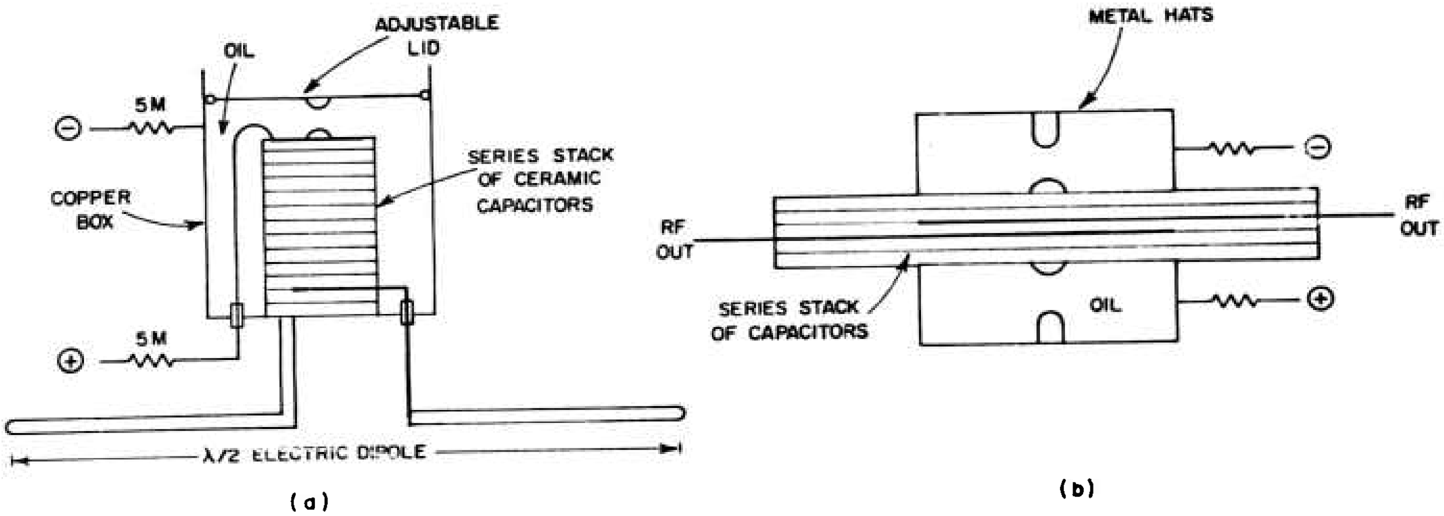


FIG. 34 CERAMIC UNIT OSCILLATORS

FIG. 35 EXPERIMENTAL CERAMIC UNIT OSCILLATOR

VI SUMMARY OF WORK IN PROGRESS

The axial radiation from the 470 Mc spark-ring transmitter, the loss in power of about three orders of magnitude in the Mark IV transmitter, and the indirect measurement of a dynamic resistance of 4 ohms per gap, may be interpreted in terms of a lack of coherence in the radiation, which in turn results from a lack of synchronization of the spark discharges. The configuration of the Mark IV transmitter was designed, inadvertently, to minimize coupling between neighboring modules. Each spark-gap is shielded from the ultraviolet flash of its neighbors by the intervening parallel-plate capacitors, and, since the angle between the neighboring linear current elements is almost zero, there is very little field coupling between modules. The fact that all units are in series does not imply phase coherency of the spark gap discharges: under some conditions we have observed a discharge of the ring in which one or more of the gaps did not participate.

In order to study the synchronization of spark-gap discharges, and in order to determine the feasibility of building an "RF laser," we have started a series of experiments with separate unit oscillators, or modules. A sketch of a unit oscillator used in current experiments is shown in Fig. 36.

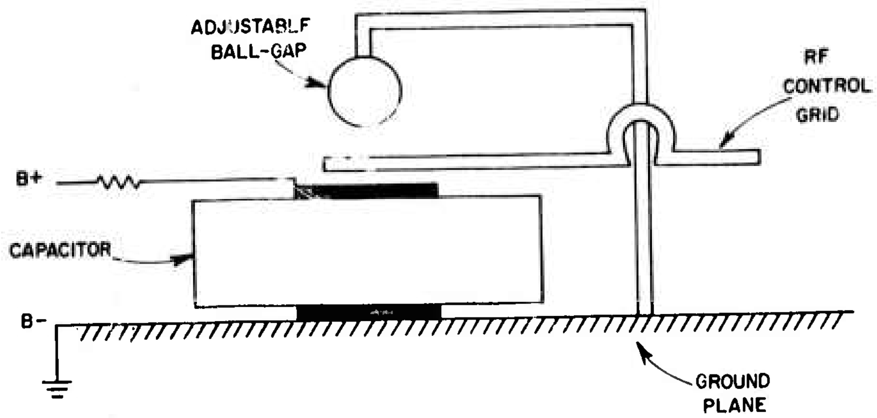


FIG. 36 UNIT OSCILLATOR USED IN SYNCHRONIZATION EXPERIMENTS

Thus far we have shown experimentally (1) that two unit oscillators will synchronize in phase at radio frequencies if the distance between them is less than a few tenths of a wavelength, regardless of whether or not the ultraviolet flash of one discharge can illuminate the other; (2) that by increasing the separation of the unit oscillators a condition can be achieved in which they will not synchronize if an opaque, non-conducting screen is placed between them, but will resume synchronization when the screen is removed; (3) that a lack of RF synchronization can occur at separations of the order of a half-wavelength or more even though the discharges appear, visibly, to occur at the same time; and (4) that there is a critical size, or minimum energy storage, which must be achieved to effect synchronization. Also, we have found that an anti-synchronization or "flip-flop" mode occurs if the B^+ supplies to the two unit oscillators are insufficiently isolated.

At the present time we are attempting to find out whether or not a separate RF transmitter can be used to trigger or synchronize two unit oscillators when the applied RF voltage is insufficient, by itself, to cause a breakdown of the gaps. The principle being tested here is whether or not coherent radiation can be induced by a radio wave applied at the resonant frequency. Such induced radiation is the basis of the laser, and if it can be achieved with macroscopic oscillators then we should be able to construct a lumped-parameter, microscopic analogue of the laser. One form of such a device would be an end-fire array of unit oscillators wherein an initial discharge of one oscillator at one end of the array starts a traveling wave down the array. The traveling wave increases in amplitude as it induces successive, coherent discharges in subsequent unit oscillators and ultimately is radiated unidirectionally at the far end of the array.

Experiments with small, scaled-down ring transmitters are continuing. If successful, these small rings can be used as remote oscillators, with the antenna connected to the oscillator by means of a single transmission line.

Unit oscillators using barium titanate capacitors are being investigated to determine if the high powers expected theoretically can be realized in practice and to determine if a monochromatic RF pulse can be generated with ceramic capacitors.

Ferrite frequency-multiplier circuits appear to be practical below 30 Mc for generating modest peak powers.

In conclusion we find that the spark transmitter schemes proposed by Landecker and co-workers, and the techniques suggested by W. Millar for biasing and frequency multiplying open many promising doors for RF power generation at HF and VHF. However, practical problems and engineering difficulties limit the performance considerably in most instances. The actual mode of operation of rings that have been built is apparently not yet well understood. The application of the proposed techniques to working transmitters is neither simple nor straightforward.

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4. W. Millar, U.K. Atomic Energy Authority, Culham, England; private communication.

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